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Internet of Things Architectures for Enhanced Living Environments

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Dedicatory

"Most of the fundamental ideas of science are essentially simple and may as a rule be expressed in a language comprehensible to everyone."
Albert Einstein

To my loving parents, Rogério and Maria da Glória, who always gave me the best they had.
Despite of difficulties, they always supported me and believed in me and my projects.
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"Train up a child in the way he should go: and when he is old, he will not depart from it."
Proverbs 22:6

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Foreword

This thesis presents the research work performed in the scope of the doctoral research programme. The doctoral research was conducted at the Ambient Assisted Living Computing and Telecommunications Laboratory (ALLab), *Universidade da Beira Interior* and also *Instituto de Telecomunicações*, Covilhã, Portugal.

The research work was supervised by Prof. Dr. Nuno M. Garcia, from the *Universidade da Beira Interior*, and co-supervised by Prof. Dr. Zdenka Babić, from University of Banja Luka, Bosnia and Herzegovina. This work was financially supported in part by the FCT/MCTES through national funds, and when applicable, co-funded EU funds under the project UIDB/EEA/50008/2020 and Operação Centro-01-0145-FEDER-000019 – C4 – Centro de Competências em Cloud Computing, co-financed by the Programa Operacional Regional do Centro (CENTRO 2020), through the Sistema de Apoio à Investigação Científica e Tecnológica – Programas Integrados de IC&DT. I would also like to acknowledge the contribution of the COST Action IC1303: AAPELE—Architectures, Algorithms and Protocols for Enhanced Living Environments and COST Action CA16226; SHELD-ON—Indoor living space improvement: Smart Habitat for the Elderly, supported by COST (European Cooperation in Science and Technology).

The research resulted in the definition and design of cost-effective, modular, and scalable architectures and Frameworks for indoor air quality monitoring based on the data acquired from low-cost sensors for enhanced living environments and occupational health. The proposed methods include several concepts such as, data acquisition, data processing, data storing, data analysis, and visualization. The proposed architectures incorporate a relevant alert manager that notifies the user when the indoor air quality is poor using pervasive and ubiquitous methods. The software Framework supports several alert methods such as smartphone notifications, SMS, and e-mail. This real-time notification Framework provides several advantages when the purpose is to achieve practical changes for enhanced living environments. On the one hand, the notification messages promote behaviour changes. These messages alert the user to act in real-time, providing measures to improve indoor environment quality. On the other hand, this real-time feature allows the building manager to recognize patterns when recurrent unhealthy events are detected to prevent them from occurring. The proposed methods incorporate mobile computing technologies such as mobile application which provide ubiquitous access to the recorded data and consequently provides an integrated solution for data analysis and visualization. Furthermore, the software framework data can be shared with medical teams to support diagnostics.

The review of the state-of-the-art has done, which results in a review paper on the IoT technologies, applications, challenges, opportunities, open-source platforms, and operating systems for enhanced living environments and healthcare systems. This review was work was fundamental in the definition of the Framework based on IoT for indoor quality supervision. The research led to the development and design of cost-effective solutions based on open-source technologies that support several advantages such as its modularity, scalability, and easy installation. The results obtained are promising, representing a meaningful contribution to enhanced living environments and occupational health.

List of Publications

List of articles included in the thesis resulting from the doctoral research:

1. **Internet of Things Architectures, Technologies, Applications, Challenges, and Future Directions for Enhanced Living Environments and Healthcare Systems: A Review**
   Gonçalo Marques, Rui Pitarma, Nuno M. Garcia and Nuno Pombo published in Electronics, MDPI, 8(2), 170; https://doi.org/10.3390/electronics8101081, September 2019 (IF 2017: 2.110, Q1 Computer Networks and Communications.)

2. **A System Based on the Internet of Things for Real-time Particle Monitoring in Buildings**
   Gonçalo Marques, Cristina Roque Ferreira and Rui Pitarma, published in the special issue Indoor Environmental Quality, International Journal of Environmental Research and Public Health, MDPI, 15(4), 821; https://doi.org/10.3390/ijerph15040821, April 2018 (IF: 2017: 2.145, Q2 Public, Environmental & Occupational Health)

3. **Indoor Air Quality Assessment Using a CO2 Monitoring System Based on Internet of Things**
   Gonçalo Marques, Cristina Roque Ferreira and Rui Pitarma, published in Journal of Medical Systems, Springer, 43 (67); https://doi.org/10.1007/s10916-019-1184-x February 2019 (IF 2017: 2.089, Q2 Health Informatics).

4. **A Cost-Effective Air Quality Supervision Solution for Enhanced Living Environments through the Internet of Things**
   Gonçalo Marques and Rui Pitarma published in Electronics, MDPI, 8(2), 170; https://doi.org/10.3390/electronics8020170, February 2019 (IF 2017: 2.110, Q1 Computer Networks and Communications.

Other publications resulting from the doctoral research not included in the thesis

1. **Health informatics for indoor air quality monitoring**
   Gonçalo Marques and Rui Pitarma published in *11th Iberian Conference on Information Systems and Technologies (CISTI 2016)*, Las Palmas, Spain, 15-18 June 2016.

2. **A survey on IoT: architectures, elements, applications, QoS, platforms and security concepts**
   Gonçalo Marques, Nuno Garcia and Nuno Pombo, chapter of the book entitled "Advances in Mobile Cloud Computing and Big Data in the 5G Era" published by Springer, November 2016.

3. **An Indoor Monitoring System for Ambient Assisted Living Based on Internet of Things Architecture**
   Gonçalo Marques and Rui Pitarma published in Int. J. Environ. Res. Public Health 2016, 13, 1152. https://doi.org/10.3390/ijerph13111152 (IF 2017: 2.145, Q2 Public, Environmental & Occupational Health).

4. **Monitoring Indoor Air Quality for Enhanced Occupational Health**
   Rui Pitarma, Gonçalo Marques and Bárbara Roque Ferreira published in Journal of Medical Systems (2017) 41: 23. https://doi.org/10.1007/s10916-016-0667-2 (IF 2017: 2.098, Q2 Health Informatics).

5. **Monitoring health factors in indoor living environments using internet of things**
   Gonçalo Marques and Rui Pitarma published in the World Conference on Information Systems and Technologies (WorldCIST 2017), Porto Santo Island, Madeira, Portugal, 11-13 April 2017.

6. **IAQ Evaluation Using an IoT CO2 Monitoring System for Enhanced Living Environments**
   Gonçalo Marques and Rui Pitarma published in the World Conference on Information Systems and Technologies (WorldCIST 2018), Naples, Italy on 27-29 March 2018.

7. **Using IoT and Social Networks for Enhanced Healthy Practices in Buildings**
   Gonçalo Marques and Rui Pitarma published in the International Conference Europe Middle East & North Africa Information Systems and Technologies to Support Learning (EMENA-ISTL'18), Fez, Morocco between 25-29 October 2018.

8. **Smartwatch-Based Application for Enhanced Healthy Lifestyle in Indoor Environments**
   Gonçalo Marques and Rui Pitarma published in the International Conference on Computational Intelligence in Information System (CIIS 2018), Brunei, 16-18 November 2018.

9. **An Internet of Things-Based Environmental Quality Management System to Supervise the Indoor Laboratory Conditions**
   Gonçalo Marques and Rui Pitarma published in Applied Sciences, MDPI, 2019, 9(3), 438, https://doi.org/10.3390/app9030438 January 2019 (IF 2017: 1.689, Q2 Engineering).

10. **Ambient Assisted Living and Internet of Things**
    Gonçalo Marques, chapter of the book entitled “Harnessing the Internet of Everything (IoE) for Accelerated Innovation Opportunities” published by IGI Global, February 2019.

11. **Promoting Health and Well-Being Using Wearable and Smartphone Technologies for Ambient Assisted Living Through Internet of Things**
    Gonçalo Marques and Rui Pitarma published in International Conference on Big Data and Networks Technologies (BDNT 2019), Leuven, Belgium, 29 April – 2 May.

12. **Air Quality through Automated Mobile Sensing and Wireless Sensor Networks for Enhanced Living Environments**
    Gonçalo Marques and Rui Pitarma published in 2019 14th Iberian Conference on Information Systems and Technologies (CISTI’2019), Coimbra, Portugal, 19-22 June.

13. **mHealth: Indoor Environmental Quality Measuring System for Enhanced Health and Well-Being Based on Internet of Things**
    Gonçalo Marques and Rui Pitarma published in J. Sens. Actuator Netw. 2019, 8(3), 43, https://doi.org/10.3390/jsan8030043 August 2019 (SJR 2018: 0.32, Q2 Computer Networks and Communications).

14. **Air Quality Monitoring using Assistive Robots for Ambient Assisted Living and Enhanced Living Environments through Internet of Things**
    Gonçalo Marques, Ivan Miguel Pires, Nuno Miranda and Rui Pitarma published in Electronics, MDPI, 8 (12), 1375; https://doi.org/10.3390/electronics8121375, September 2019 (IF 2017: 2.110, Q1 Computer Networks and Communications.)

15. **A Comprehensive Review on Indoor Air Quality Monitoring Systems for Enhanced Public Health**
    Jagriti Saini, Maitreyee Dutta and Gonçalo Marques published in Sustainable Environment Research, Springer, 30 (6), https://doi.org/10.1186/s42834-020-0047-y, January 2020 (SJR:0.620, Q2 Environmental Engineering.)

16. **Internet of Things and Enhanced Living Environments: Measuring and Mapping Air Quality Using Cyber-Physical Systems and Mobile Computing Technologies**
    Gonçalo Marques, Nuno Miranda, Akash Kumar Bhoi, Begonya Garcia-Zapirain, Sofiane Hamrioui, Isabel de la Torre Díez in Sensors, MDPI, 20 (3), 720; https://doi.org/10.3390/s20030720, January 2020 (IF 2019: 3.031, Q2 Electrical and Electronic Engineering.)

17. **Internet of Things for Enhanced Smart Cities: A Review, Roadmap and Case Study on Air Quality Sensing**
    Gonçalo Marques and Rui Pitarma published in 2019, Society with Future: Smart and Liveable Cities: First EAI International Conference, SC4Life 2019, Braga, Portugal, December 4–6, 2019.

18. **Particulate Matter Assessment in Association with Temperature and Humidity: An Experimental Study on Residential Environment**
    Jagriti Saini, Maitreyee Dutta and Gonçalo Marques published in 2019, International Conference on IoT Inclusive Life (ICIIL 2019), NITTTR Chandigarh, India, December 19–20, 2019.

19. **Internet of Things for Enhanced Living Environments, Health and Well-Being: Technologies, Architectures and Systems**
    Gonçalo Marques, Jagriti Saini, Ivan Miguel Pires, Nuno Miranda and Rui Pitarma, chapter of the book entitled "Handbook of Wireless Sensor Networks: Issues and Challenges in Current Scenario's" published by Springer, February 2020.

Resumo

Ambient Assisted Living (AAL) é uma área de investigação multidisciplinar emergente que visa a construção de um ecossistema de diferentes tipos de sensores, microcontroladores, dispositivos móveis, redes sem fios e aplicações de software para melhorar os ambientes de vida e a saúde ocupacional. Existem muitos desafios no desenvolvimento e na implementação de um sistema AAL, como a arquitetura do sistema, interação humano-computador, ergonomia, usabilidade e acessibilidade. Existem também problemas sociais e éticos, como a aceitação por parte dos utilizadores mais vulneráveis e a privacidade e confidencialidade, que devem ser uma exigência de todos os dispositivos AAL. De facto, também é essencial assegurar que a tecnologia não substitua o cuidado humano e seja usada como um complemento essencial.

A Internet das Coisas (IoT) é um paradigma em que os objetos estão conectados à Internet e suportam recursos sensoriais. Tendencialmente, os dispositivos IoT devem ser omnipresentes, reconhecer o contexto e ativar os recursos de inteligência ambiente intimamente relacionados ao AAL. Os avanços tecnológicos permitem definir novas ferramentas avançadas e plataformas para monitorização de saúde em tempo real e tomada de decisão no tratamento de várias doenças. A IoT é uma abordagem adequada para construir sistemas de saúde sendo que oferece uma plataforma para serviços de saúde ubíquos, usando, por exemplo, sensores portáteis para recolha e transmissão de dados e *smartphones* para comunicação. Apesar do potencial do paradigma e tecnologias IoT para o desenvolvimento de sistemas de saúde, muitos desafios continuam ainda por ser resolvidos. A direção e o impacto das soluções IoT na economia não está claramente definido existindo, portanto, barreiras à adoção imediata de produtos, serviços e soluções de IoT.

Os ambientes de vida são caracterizados por diversas fontes de poluentes. Consequentemente, a qualidade do ar interior é reconhecida como uma variável fundamental a ser controlada de forma a melhorar a saúde e o bem-estar. É importante referir que tipicamente a maioria das pessoas ocupam mais de 90% do seu tempo no interior de edifícios e que a má qualidade do ar interior afeta negativamente o desempenho e produtividade.

É necessário que as equipas de investigação continuem a abordar os problemas de qualidade do ar visando a adoção de legislação e mecanismos de inspeção que atuem em tempo real para a melhoraria da saúde e qualidade de vida, tanto em locais públicos como escolas e hospitais e residências particulares de forma a aumentar o rigor das regras de construção de edifícios. Para tal, é necessário utilizar mecanismos de monitorização em tempo real de forma a possibilitar a análise correta da qualidade do ambiente interior para garantir ambientes de vida saudáveis. Na maioria dos casos, intervenções simples que podem ser executadas pelos proprietários ou

ocupantes da residência podem produzir impactos positivos substanciais na qualidade do ar interior, como evitar fumar em ambientes fechados e o uso correto de ventilação natural.

Um sistema de monitorização e avaliação da qualidade do ar interior ajuda na deteção e na melhoria das condições ambiente. A avaliação local e distribuída das concentrações químicas é significativa para a segurança (por exemplo, deteção de fugas de gás e supervisão dos poluentes) bem como para controlar o aquecimento, ventilação, e sistemas de ar condicionado (HVAC) visando a melhoria da eficiência energética. A monitorização em tempo real da qualidade do ar interior fornece dados fiáveis para o correto controlo de sistemas de automação de edifícios e deve ser assumida com uma plataforma de apoio à decisão no que se refere ao planeamento de intervenções para ambientes de vida melhorados. No entanto, os sistemas de monitorização atualmente disponíveis são de alto custo e apenas permitem a recolha de amostras aleatórias que não são providas de informação temporal. A maioria das soluções disponíveis no mercado permite apenas a acesso ao histórico de dados que é limitado à memória do dispositivo e exige procedimentos de download e manipulação de dados com software proprietário. Desta forma, o desenvolvimento de sistemas inovadores de monitorização ambiente baseados em tecnologias ubíquas e computação móvel que permitam a análise em tempo real torna-se essencial.

A Tese resultou na definição e no desenvolvimento de arquiteturas para monitorização da qualidade do ar baseadas em IoT. Os métodos propostos são de baixo custo e recorrem a estruturas modulares e escaláveis para proporcionar ambientes de vida melhorados. As arquiteturas propostas abordam vários conceitos, incluindo aquisição, processamento, armazenamento, análise e visualização de dados. Os métodos propostos incorporam *Frameworks* de gestão de alertas que notificam o utilizador em tempo real e de forma ubíqua quando a qualidade do ar interior é deficiente. A estrutura de software suporta vários métodos de notificação, como notificações remotas para *smartphone*, SMS (*Short Message* Service) e *e-mail*. O método usado para o envio de notificações em tempo real oferece várias vantagens quando o objetivo é alcançar mudanças efetivas para ambientes de vida melhorados. Por um lado, as mensagens de notificação promovem mudanças de comportamento. De facto, estes alertas permitem que o gestor do edifício e os ocupantes reconheçam padrões da qualidade do ar e permitem também um correto planeamento de intervenções de forma evitar situações em que a qualidade do ar é deficiente. Por outro lado, o sistema proposto incorpora tecnologias de computação móvel, como aplicações móveis, que fornecem acesso omnipresente aos dados de qualidade do ar e, consequentemente, fornecem soluções completas para análise de dados. Além disso, os dados são armazenados e podem ser partilhados com equipas médicas para ajudar no diagnóstico.

A análise do estado da arte resultou na elaboração de um artigo de revisão sobre as tecnologias, aplicações, desafios, plataformas e sistemas operativos que envolvem a criação de arquiteturas IoT. Esta revisão foi um trabalho fundamental na definição das arquiteturas propostas baseado em IoT para a supervisão da qualidade do ar interior. Esta pesquisa conduz a um desenvolvimento de arquiteturas IoT de baixo custo com base em tecnologias de código aberto que operam como um sistema Wi-Fi e suportam várias vantagens, como modularidade, escalabilidade e facilidade de instalação. Os resultados obtidos são muito promissores, representando uma contribuição significativa para ambientes de vida melhorados e saúde ocupacional.

O material particulado (PM) é uma mistura complexa de partículas sólidas e líquidas de substâncias orgânicas e inorgânicas suspensas no ar e é considerado o poluente que afeta mais pessoas. As partículas mais prejudiciais à saúde são as $\leq PM_{10}$ (diâmetro de 10 micrómetros ou menos), que podem penetrar e fixarem-se dentro dos pulmões, contribuindo para o risco de desenvolver doenças cardiovasculares e respiratórias, bem como de cancro do pulmão. Tendo em consideração os efeitos negativos para a saúde da exposição ao PM foi desenvolvido numa primeira fase uma arquitetura IoT para monitorização automática dos níveis de PM. Esta arquitetura é um sistema que permite monitorização de PM em tempo real e uma ferramenta de apoio à tomada de decisão. A solução é composta por um protótipo de hardware para aquisição de dados e um portal Web desenvolvido em .NET para consulta de dados. Este sistema é baseado em tecnologias de código aberto com várias vantagens em comparação aos sistemas existentes, como modularidade, escalabilidade, baixo custo e fácil instalação. Os dados são armazenados numa base de dados desenvolvida em SQL SERVER e são enviados com recurso a serviços Web. Os resultados mostram a capacidade do sistema de analisar em tempo real a qualidade do ar interior e o potencial da Framework Web para o planeamento de intervenções com o objetivo de garantir condições seguras, saudáveis e confortáveis.

Associações de altas concentrações de dióxido de carbono (CO_2) com défice de produtividade no trabalho e aumento de problemas de saúde encontram-se bem documentadas. Existe também uma correlação evidente entre altos níveis de CO_2 e altas concentrações de poluentes no ar interior. Tendo em conta a influência significativa do CO_2 para a construção de ambientes de vida melhorados desenvolveu-se uma solução de monitorização em tempo real de CO_2 com base na arquitetura de IoT. A arquitetura proposta permite também o envio de notificações em tempo real para melhorar a saúde ocupacional e proporcionar um ambiente de vida interior seguro e saudável. O CO_2 foi selecionado, pois é fácil de medir e é produzido em quantidade (por pessoas e equipamentos de combustão). Assim, pode ser usado como um indicador de outros poluentes e, portanto, da qualidade do ar em geral. O método proposto é composto por um protótipo de hardware para aquisição de dados, um software Web e uma aplicação smartphone para consulta de dados. Esta arquitetura é baseada em tecnologias de código aberto e os dados recolhidos são armazenados numa base de dados SQL SERVER. A Framework móvel permite não só consultar em tempo real os últimos dados recolhidos, receber notificações com o objetivo de avisar o utilizador quando a qualidade do ar está deficiente, mas também para configurar alertas. Os resultados mostram que a Framework móvel fornece

não apenas acesso fácil aos dados da qualidade do ar em tempo real, mas também permite ao utilizador manter o histórico de parâmetros. Assim este sistema permite ao utilizador analisar de maneira precisa e detalhada o comportamento da qualidade do ar interior.

Por último, é proposta uma arquitetura para monitorização de vários parâmetros da qualidade do ar, como NH_3 (amoníaco), CO (monóxido de carbono), NO_2 (dióxido de azoto), C_3H_8 (propano), C_4H_{10} (butano), CH_4 (metano), H_2 (hidrogénio) e C_2H_5OH (etanol). Esta arquitetura é composta por um protótipo de hardware que incorpora unicamente o sensor MICS-6814 como unidade de deteção. O controlo das concentrações destes poluentes é extremamente relevante para proporcionar ambientes de vida melhorados. Esta solução tem base na *Cloud* sendo que os dados recolhidos são enviados para a plataforma *ThingSpeak*. Esta Framework combina sensibilidade, flexibilidade e precisão de medição em tempo real, permitindo uma evolução significativa dos atuais sistemas de monitorização da qualidade do ar. Os resultados mostram que este sistema fornece acesso fácil, intuitivo e rápido aos dados de qualidade do ar bem como notificações essenciais em situações de qualidade do ar deficiente de forma a planear intervenções em tempo útil e melhorar a saúde ocupacional. Esses dados podem ser acedidos pelos médicos para apoiar diagnósticos e correlacionar os sintomas e problemas de saúde dos pacientes com o ambiente em que estes vivem.

Como trabalho futuro, os resultados reportados nesta Tese podem ser considerados um ponto de partida para o desenvolvimento de um sistema seguro para partilha de dados com profissionais de saúde de forma a servir de suporte à decisão no diagnóstico.

Palavras-Chave

Ambientes de Vida Assistida, Ambientes de Vida Melhorados, Aplicações Móveis, Computação Móvel, Computação Ubíqua, Internet das Coisas, Monitorização, Notificações remotas, Qualidade do ar, Sistemas Perversivos, Software de Código Aberto.

Resumo Alargado

Introdução:

Este capítulo apresenta o resumo alargado do trabalho de investigação da Tese de doutoramento denominada por "*Internet of Things Architectures for Enhanced Living Environments*", escrito em Língua Portuguesa. Primeiramente é realizado o enquadramento do trabalho de investigação, seguido da análise dos problemas abordados, argumento e principais contribuições.

Seguidamente é realizado o resumo das principais contribuições do trabalho e por último são apresentadas as principais conclusões e trabalho futuro.

Enquadramento da Tese:

A ideia base da Internet das Coisas (IoT) é a presença generalizada de uma extensa variedade de objetos com capacidade de interação e cooperação para alcançar um objetivo comum [1]. Espera-se que a IoT tenha um grande impacto significativo em vários aspetos da vida quotidiana e este conceito será utilizado em muitas aplicações, tais como domótica, vida assistida, e-saúde. A IoT é também um paradigma emergente e adequado para fornecer recursos computacionais que visam a criação de aplicações de software revolucionárias [2].

Os sistemas IoT interagem através de tecnologias de comunicação sem fios tais como RFID (*Radio-Frequency Identification*), NFC (*Near Field Communication*), ZigBee, WSN (*Wireless sensor network*), DSL (*Digital Subscriber Line*), WLAN (*wireless local area network*), WiMax (*Worldwide Interoperability for Microwave Access*), UMTS (*Universal Mobile Telecommunications System*), GPRS (*General Packet Radio Service*) e LTE (*Long-Term Evolution*).

A IoT apresenta vários desafios a serem resolvidos, tais como segurança e privacidade, problemas relacionados com Big Data e questões de arquitetura de sistemas, além dos conhecidos desafios de redes de sensores (WSN), incluindo eficiência energética, protocolos e qualidade de serviço (QoS) [2]. Aplicações industriais, monitorização e controlo de água, casas inteligentes, previsão de desastres naturais, aplicações médicas, aplicações de agricultura, sistemas de transporte e cidades inteligentes são exemplos de aplicações de IoT [3].

Os principais elementos da IoT são: identificação, sensorização (recolha de dados do ambiente em que o dispositivo IoT está inserido), comunicação, computação, serviços e semântica. A identificação é essencial para o desenvolvimento do IoT, e é importante para garantir o correto reconhecimento dos objetos, a fim de fazer corresponder os serviços com a sua procura. Existem vários métodos de identificação, tais como EPC - *Electronic Product Codes* e uCode-*ubiquitous Code*. A identificação dos objetos refere-se ao seu nome ou designação e o endereçamento refere-se ao seu endereço IP para comunicação em rede. Atualmente existe uma grande variedade de métodos de endereçamento tais como IPv4, IPv6 e 6LoWPAN que fornece compressão em cabeçalhos IPv6 [4]. Na IoT, a sensorização refere-se à aquisição de dados do ambiente e ao seu envio para uma base de dados, local, remota ou na *Cloud*. Como exemplo de sensores em IoT podem-se definir sensores inteligentes ou sensores usáveis. A comunicação é parte integrante de todos os dispositivos IoT, sendo esta limitada pela natureza das próprias tecnologias, como por exemplo, a duração da bateria ou a reduzida gama de transmissão de dados. Protocolos como Wi-Fi, ZigBee, GSM, GPRS, UMTS, 3G, LTE e 5G [5] fornecem capacidade adequada para comunicação entre os dispositivos IoT. O padrão IEEE 802.15.4e foi lançado pelo IEEE em 2012 para melhorar e adicionar funcionalidades ao padrão anterior 802.15.4, de forma a atender às necessidades emergentes de aplicações industriais embebidas [6]. Há também outras tecnologias usadas para comunicações de proximidade como RFID [7], NFC [8] e BLE (*Bluetooth Low Energy*) [9]. Um protocolo para computação simplificada na identificação de colisões em comunicações por RFID denominado por CWT+, foi proposto por [10]. O uso de etiquetas NFC flexíveis e de baixo custo permitem que objetos do quotidiano comuniquem com *smartphones* e computadores de forma a participarem ativamente em ecossistemas IoT [11]. O protocolo BLE oferece recursos adequados para tecnologias de comunicação de baixa tensão em IoT e podem ser aplicados em redes 6LoWPAN [11]. A IoT é implementada usando várias plataformas de hardware como por exemplo o Arduino [12], Intel Galileo [13], Raspberry Pi [14] ou o ESP8266 [15]. As plataformas de computação na *Cloud* também constituem uma parte computacional importante no paradigma da IoT porque conferem vantagens no armazenamento e/ou processamento de dados online.

Os diferentes serviços de IoT podem ser categorizados como serviços de identificação, serviços de agregação de informação, serviços colaborativos e serviços ubíquos [16].Os serviços de identificação são focados na identificação de objetos, enquanto os serviços de agregação recolhem dados sensoriais e enviam-nos para a aplicação de *backend*. Além disso, os serviços colaborativos são usados para transformar os dados obtidos numa decisão que deverá resultar numa ação, enquanto os serviços ubíquos visam fornecer serviços colaborativos a qualquer momento, a qualquer pessoa e em qualquer lugar.

A semântica corresponde à capacidade de extrair conhecimento de dispositivos IoT para o fornecimento de serviços. Assim, como exemplos de tecnologias da Semântica Web podem ser referidos o *Resource Description Framework* (RDF) e a *Ontology Web Language* (OWL) [17]. Em 2011, o consórcio *World Wide Web* (W3C) adotou o formato *Efficient XML Interchange* (EXI) [18] como uma recomendação. O EXI converte mensagens XML em binário para reduzir a largura de banda e minimizar o tamanho de armazenamento necessário.

O Ambiente de Vida Assistida (ou *Ambient Assisted Living*) (AAL) é um campo multidisciplinar emergente que visa o desenvolvimento de um ecossistema de diferentes tipos de sensores, computadores, dispositivos móveis, redes sem fio e aplicações de software para monitorização de saúde pessoal e sistemas de telemedicina [19]. Atualmente, diferentes soluções AAL incorporam vários sensores de medição de peso, pressão arterial, glicose, oxigénio, temperatura, localização e posição, que geralmente usam tecnologias de comunicação sem fios, como ZigBee, Bluetooth, Ethernet e Wi-Fi.

Existem diversos desafios na conceção e implementação de um sistema AAL, como a arquitetura da informação, design de interação, interação homem-computador, ergonomia, usabilidade e acessibilidade [20]. Há também problemas sociais e éticos, como a aceitação pelos adultos mais vulneráveis, privacidade e confidencialidade que devem ser uma exigência de todos os dispositivos AAL. De facto, também é essencial assegurar que a tecnologia não substitua o cuidado humano e devendo ser utilizada como complemento essencial.

O conceito de "cidade inteligente" foi recentemente introduzido como uma metodologia estratégica para abranger os fatores de produção urbanos modernos num quadro comum e, em particular, para destacar a importância das tecnologias da informação e comunicação (TIC) nos últimos 20 anos para melhorar o perfil competitivo de uma cidade [21]. Atualmente, as cidades enfrentam desafios e problemas complexos para responder aos objetivos de desenvolvimento socioeconômico e qualidade de vida. O conceito de "cidades inteligentes" corresponde à resposta a esses desafios [22]. A cidade inteligente está diretamente relacionada a uma estratégia emergente para mitigar os problemas gerados pelo crescimento populacional urbano e pela rápida urbanização [23]. A questão mais relevante em cidades inteligentes é a não interoperabilidade de tecnologias heterogêneas. A IoT pode fornecer interoperabilidade para construir uma plataforma de escala urbana unificada para cidades inteligentes [24]. A implementação da cidade inteligente causará impactos em níveis distintos sobre ciência, tecnologia, competitividade e sociedade, mas também causará problemas éticos. Uma cidade inteligente precisa fornecer acesso a informações detalhadas, essas informações estão disponíveis em uma escala espacial pormenorizada, onde os indivíduos podem ser identificados [25]. A IoT tem um potencial relevante para criar novas aplicações e serviços da vida real para o contexto da cidade inteligente [26].

As condições ambientais têm um impacto significativo na saúde ocupacional. Em particular, os ambientes interiores assumem um papel fundamental na saúde e bem-estar sendo que as pessoas ocupam tipicamente cerca de 90% do seu tempo no interior de edifícios [27].

Nos EUA, a qualidade do ar é regulada pela Agência de Proteção Ambiental (EPA). A EPA constatou que os níveis de poluentes em ambientes interiores podem ser até 100 vezes superiores ao nível de poluentes do ar exterior e classificou a qualidade do ar interior como um dos 5 principais riscos para a saúde pública [27].

O problema da qualidade do ar é de extrema importância, afetando especialmente de forma grave as pessoas mais pobres do mundo que são mais vulneráveis, apresentando-se como um problema crítico para a saúde mundial, como o uso de tabaco ou a questão das doenças sexualmente transmissíveis [28].

As equipas de investigação devem continuar a centrar-se nos problemas da qualidade do ar de forma a adaptar legislação, inspeção e criação de mecanismos que atuem em tempo real para melhorar a saúde pública em locais públicos, como escolas e hospitais, e aumentar ainda mais a rigorosidade das regras de construção de edifícios. Para este efeito, é necessário utilizar mecanismos de monitorização em tempo real para tornar possível a análise correta da qualidade do ar de forma a garantir um ambiente saudável, pelo menos, em espaços de utilização pública.

Na maioria dos casos, intervenções simples que podem ser executadas pelos ocupantes podem produzir impactos positivos substanciais sobre a qualidade do ar interior. Por exemplo, evitar fumar em espaços interiores e o uso de ventilação natural são comportamentos essenciais que devem ser ensinados a crianças através de programas educativos [29].

A monitorização em tempo real das condições ambientais, em geral, e da qualidade do ar, em particular, permite criar uma base de dados com referência temporal que pode ser usada para analisar comportamentos nocivos para a saúde dos ocupantes. Um sistema automático de monitorização e de notificações em tempo real oferece várias vantagens quando o propósito é atingir mudanças efetivas para ambientes de vida melhorados. Por um lado, as mensagens de notificação promovem mudanças de comportamento. De facto, essas mensagens alertam o ocupante para agir em tempo real, fornecendo medidas para melhorar a qualidade ambiente. Por outro lado, esse recurso em tempo real permite que o gestor do edifício reconheça padrões quando eventos recorrentes não saudáveis são detetados e a consequente implementação de intervenções para evitar que estes ocorram. Para além disso, estes dados podem ser partilhados com equipas médicas para suporte ao diagnóstico. Tipicamente as pessoas ocupam a maior parte do tempo em ambientes fechados, portanto, é necessário monitorizar a qualidade do ar interior e planear intervenções para ambientes de vida melhorados e aumentar a produtividade.

O âmbito desta tese consiste no uso de metodologias IoT para o desenvolvimento de arquiteturas de monitorização da qualidade do ar para ambientes de vida melhorados. Estes sistemas incorporam formas perversivas de acesso aos dados através de computação móvel. Os sistemas propostos são de baixo custo de construção, instalação, configuração, modulares, escaláveis e de fácil acesso aos dados de monitorização em tempo real através da Framework Web ou móvel. Estes sistemas visam a criação de ambientes de vida melhorados, mas também são elementos essenciais para a implementação do conceito de cidades inteligentes.

Descrição do Problema e Objetivos da Investigação

O problema estudado nesta Tese resultou na definição e no desenvolvimento de arquiteturas IoT de baixo custo com recurso a estruturas modulares e escaláveis para monitorização da qualidade do ar com base em IoT. As arquiteturas propostas incorporam uma *Framework* de gestão de alertas que notificam o utilizador em tempo real e de forma ubíqua quando a qualidade do ar é deficiente. A estrutura de software suporta vários métodos de notificação, como notificações remotas para *smartphone*, SMS e *e-mail*. Este mecanismo de notificações em tempo real oferece várias vantagens quando o objetivo é alcançar mudanças efetivas para ambientes de vida melhorados. Os ambientes de vida são caracterizados por diversas fontes de poluentes. Consequentemente, a qualidade do ar interior é reconhecida como uma variável crucial a ser controlada de forma a melhorar a saúde e o bem-estar. É importante referir que tipicamente a maioria das pessoas ocupam mais de 90% do seu tempo no interior de edifícios e que a má qualidade do ar interior afeta negativamente o desempenho e produtividade.

A adoção de sistemas e técnicas avançadas de monitorização que visam a criação de uma base de dados com referência temporal para a correta avaliação dos ambientes de vida é uma ferramenta importante para o suporte à decisão e ao diagnóstico médico. Para tal, é necessário utilizar soluções de supervisão em tempo real que incorporem sistemas que permitam uma análise correta da qualidade do ar para garantir um ambiente saudável em pelo menos espaços de uso público. Na maioria dos casos, intervenções simples fornecidas por proprietários de residências podem produzir impactos positivos substanciais na qualidade do ar interior.

A monitorização em tempo real de ambientes de vida assistida é um tema de elevada importância para a criação de outro tipo de aplicações que recorram a dados que são recolhidos por estes sistemas. Estes dados podem ser utilizados para a suportar uma correta automatização de edifícios, melhorar a eficiência energética e como consequência diminuir os gases de efeito de estufa. Atualmente, a maioria das soluções de monitorização de ambientes interiores disponíveis no mercado são não só extremamente complexas e caras, bem como o seu funcionamento é baseado em amostragem aleatória. No entanto, essas técnicas são restritivas porque fornecem apenas informações relacionadas a uma amostragem específica e são desprovidas de dados espácio-temporais. Algumas dessas soluções são compactas, portáteis e suportam o registo de dados no próprio equipamento, mas não permitem o acesso aos dados em tempo real para os gestores de edifícios de forma a permitir uma intervenção rápida e eficiente para melhorar a qualidade do ar interior. Além disso, essas soluções não suportam compatibilidade móvel para consulta de dados ou notificações.

Por um lado, a maior parte dos equipamentos presente no mercado armazena o histórico de dados recolhidos na memória do dispositivo e exige procedimentos específicos para o download e manipulação de dados com software proprietário. Por outro lado, essas soluções são extremamente precisas e projetadas para atividades industriais. No entanto, a supervisão de ambientes interiores assume um papel essencial para a melhoria da saúde ocupacional e bem-estar. Consequentemente, o desenvolvimento de novos métodos e arquiteturas de monitorização da qualidade do ar interior baseados em tecnologias de comunicação sem fios que ofereçam acesso, visualização e análise de dados em tempo real é particularmente relevante.

O principal objetivo desta Tese é o desenvolvimento de novos métodos e arquiteturas IoT para monitorização de ambientes interiores que sejam de baixo custo, fácil instalação, modulares e escaláveis com recurso a tecnologias de comunicação sem fios e computação móvel. A arquitetura da solução desenvolvida incorpora vários conceitos, incluindo aquisição, processamento, armazenamento, análise e visualização de dados. O método proposto incorpora uma Framework de gestão de alertas que notifica o utilizador em tempo real e de forma ubíqua quando a qualidade do ar é deficiente.

Este mecanismo de notificações em tempo real oferece várias vantagens quando o objetivo é alcançar mudanças efetivas para ambientes de vida melhorados. As mensagens de notificação promovem mudanças de comportamento.

Nesta Tese são propostas várias arquiteturas IoT para monitorização de ambientes interiores, nomeadamente para a avaliação e análise da qualidade do ar. Foram estudados vários problemas nomeadamente a supervisão de matéria particulada (PM), CO_2 e outros parâmetros específicos da qualidade do ar, como NH_3 (amoníaco), CO (monóxido de carbono), NO_2 (dióxido de azoto), C_3H_8 (propano), C_4H_{10} (butano), CH_4 (metano), H_2 (hidrogénio) e C_2H_5OH (etanol).

A fim de organizar o trabalho de investigação e atingir o objetivo principal da tese foram estabelecidos um conjunto de objetivos intermédios importantes:

1. De modo a compreender e avaliar corretamente o paradigma IoT nomeadamente a nível das diversas oportunidades para inúmeras aplicações, particularmente no âmbito dos sistemas de saúde, esta Tese começou com a revisão do estado da arte. Esta revisão fez uma análise do atual estado da arte em arquiteturas de IoT para ambientes de vida melhorados e sistemas de saúde com foco nas tecnologias, aplicações de software, desafios, oportunidades, plataformas de código aberto e ferramentas de software.
2. Seguidamente, como segundo objetivo intermédio foi desenvolvida uma arquitetura IoT para monitorização de qualidade do ar de PM que inclui uma Framework Web para consulta e histórico de dados e notificações.
3. Como terceiro objetivo intermédio, foi realizado o desenvolvimento de uma Framework para de avaliação da qualidade do ar com recurso a supervisão de dióxido de carbono. Esta Framework é composta por um sistema de monitorização, aplicação Web e aplicação móvel para acesso aos dados e vários tipos de alertas como por exemplo, SMS, e-mail e notificações remotas através da aplicação móvel.
4. Por último, o quarto objetivo intermédio consiste na definição e desenvolvimento de uma solução IoT para supervisão de vários parâmetros da qualidade do ar em que os dados são armazenados na *Cloud*. Esta Framework deve incorporar sensibilidade, flexibilidade e precisão de medição em tempo real, permitindo uma evolução significativa dos atuais sistemas de qualidade do ar. Este método deverá propor um sistema de acesso fácil, intuitivo e rápido aos dados de qualidade do ar bem como notificações essenciais em situações de qualidade do ar deficiente para fornecer intervenção em tempo real e melhorar a saúde ocupacional.

A *Framework* de supervisão de ambientes interiores desenhada como resultado da investigação assume elevada importância para a criação de ambientes de vida melhorados. Esta Tese é também importante para a monitorização remota de ambientes de vida melhorados e permite que os dados podem ser consultados pelo cuidador ou da equipa médica para suporte ao diagnóstico. O sistema de notificações permite acompanhar em tempo real situações em que o ambiente apresenta deficiências de forma a agir em tempo real para a criação de ambientes de vida melhorados e saúde ocupacional.

Argumento da Tese

Esta Tese propõe novos métodos e arquiteturas de baixo custo, modulares, escaláveis e de fácil instalação baseadas na IoT para monitorização da qualidade do ar com base nos dados obtidos através de sensores de baixo custo para ambientes de vida melhorados. Especificamente, o argumento da Tese é:

> A supervisão automática das condições ambiente deve ser assumida como um desafio complexo sendo que a qualidade ambiente tem um impacto direto na saúde e bem-estar. Contudo, não há métodos estruturados para a supervisão em tempo-real que incorporem uma Framework de gestão de alertas com capacidades de notificação em tempo real e de forma ubíqua quando a qualidade do ambiente interior é deficiente. A definição de uma nova arquitetura que suporte vários métodos de notificação, como notificações remotas para *smartphone*, SMS e *e-mail* contribui significativamente na criação de ambientes melhorados e da saúde ocupacional. Estas notificações promovem mudanças de comportamento e permitem a identificação de padrões da qualidade ambiente de forma a proceder a um correto planeamento de intervenções para proporcionar ambientes de vida melhorados. Este sistema deve incorporar tecnologias de computação móvel que forneçam acesso ubíquo aos dados e, consequentemente, ferramentas avançadas para consulta e avaliação de dados. Os dados são armazenados e podem ser partilhados com equipas médicas para suporte ao diagnóstico.

De forma a atingir os objetivos da Tese, foi realizada uma revisão sobre arquiteturas, aplicações desafios e oportunidades do paradigma IoT. Esta revisão sobre os diferentes conceitos envolvidos no desenvolvimento de soluções IoT foi realizada com especial ênfase na área ligada ao desenho de soluções para ambientes de vida melhorados e saúde ocupacional. Seguidamente foram desenvolvidas novos métodos e arquiteturas IoT para aquisição, transmissão e armazenamento de dados. Após a aquisição de dados, foram desenvolvidas ferramentas avançadas de exploração de dados. Estas ferramentas foram desenhadas com recurso a tecnologias de computação móvel com vista à conceção de um sistema ubíquo que permita o acesso aos dados em qualquer momento e em qualquer lugar.

Principais Contribuições

Nesta secção é realizada uma descrição sucinta das principais contribuições científicas dos trabalhos de investigação da Tese.

A primeira contribuição está relacionada com a revisão do estado da arte de arquiteturas IoT para ambientes de vida melhorados e sistemas de saúde. Esta revisão faz uma síntese temática e uma comparação entre plataformas IoT e permite identificar traços e lacunas comuns que abrem novas direções de investigação. Esta contribuição foi publicada na revista Electronics (MDPI) 2019, 8, 1081 (IF 2017: 2.110, Q1 Computer Networks and Communications).

A segunda contribuição desta Tese é a conceção e desenvolvimento de uma arquitetura IoT para monitorização de PM que incorpora uma Framework Web para consulta, histórico, análise de dados e notificações. Esta contribuição foi publicada na revista Int. J. Environ. Res. Public Health (MDPI) 2018, 13, 1152 (IF 2017: 2.145, Q2 Public, Environmental & Occupational Health).

A terceira contribuição desta Tese é a proposta de uma arquitetura IoT para de avaliação da qualidade do ar com recurso a supervisão de dióxido de carbono. Esta arquitetura é constituída por um sistema de monitorização, Framework Web e aplicação móvel para acesso aos dados e vários tipos de alertas como por exemplo, SMS, e-mail e notificações remotas através da aplicação móvel. Esta contribuição foi publicada na revista Journal of Medical Systems (Springer) 2019, 43, 67 (IF 2017: 2.089, Q2 Health Informatics).

A quarta contribuição desta Tese é o desenvolvimento de um método de supervisão de vários parâmetros da qualidade do ar em que os dados são armazenados na Cloud. Esta arquitetura fornece acesso fácil, intuitivo e rápido aos dados de qualidade do ar bem como notificações essenciais em situações de qualidade do ar deficiente para fornecer intervenção em tempo real e melhorar a saúde ocupacional. Esta contribuição foi publicada na revista Electronics (MDPI) 2019, 8, 170 (IF 2017: 2.110, Q1 Computer Networks and Communications).

Estado da arte

Na primeira parte da Tese são apresentadas as principais conclusões da revisão do estado da arte sobre arquiteturas IoT para ambientes de vida melhorados e sistemas de saúde com especial ênfase nas tecnologias, aplicações, desafios e direções futuras.

Internet das Coisas para ambientes de vida melhorados e sistemas de saúde

Atualmente, existem diferentes sistemas de saúde baseados em arquiteturas IoT que incorporam várias tecnologias para monitorização de parâmetros ambientais e do estado fisiológico de indivíduos usando diferentes tecnologias de comunicação sem fios, como ZigBee, 3G, Bluetooth, Ethernet e Wi-Fi [30]. Por um lado, a monitorização dos parâmetros fisiológicos fornece a perceção do estado clínico e é particularmente importante para indivíduos mais vulneráveis, como idosos e recém-nascidos, de forma a detetar sintomas em tempo útil. Por outro lado, as condições ambientais também desempenham um papel importante no bem-estar e podem ser monitorizadas em tempo real para detetar e evitar situações não saudáveis. Ambos os dados monitorizados (fisiológicos e ambientais) podem ser analisados pelos médicos, a fim de apoiar os diagnósticos clínicos. Em particular, a qualidade do ar é um fator significativo a ser monitorizado e controlado em tempo real para ambientes de vida melhorados e saúde ocupacional, uma vez que as pessoas ocupam cerca de 90% do seu tempo dentro dos edifícios [27]. A avaliação da qualidade do ar apoia a tomada de decisões sobre possíveis intervenções para melhorar a produtividade e o ambiente interior, identificando múltiplas situações ou hábitos que afetam o bem-estar.

Há muitos problemas em aberto no planeamento e na implementação de sistemas de saúde perversivos, como usabilidade, interface do utilizador, estrutura de dados, design ubíquo, ergonomia e acesso aos dados [20]. Contudo, existe uma série de questões sociais e éticas, como a aceitação por utilizadores mais vulneráveis, privacidade e a confidencialidade das informações monitorizadas por estes sistemas de saúde [31]. É igualmente imperativo garantir que a inovação não substitua o cuidado humano, e que a tecnologia deva ser usada para apoiar decisões médicas e monitorizar o estado de saúde de pacientes em qualquer lugar e a qualquer momento [32].

Até 2050, 20% da população total terá 60 anos de idade ou mais [33], o que resultará num aumento de doenças e custos relacionados com os cuidados de saúde [34]. É de citar que 87% da população em geral prefere permanecer em sua casa e ter sistemas de saúde personalizados mesmo suportando o custo dos cuidados de enfermagem em vez de se mudar para um lar de idosos [35]. A IoT oferece suporte a sistemas de saúde que permitem que as pessoas permaneçam em casa e sejam monitorizadas em tempo real, em vez de serem transferidas para lares de idosos ou clínicas. Diversas atividades de monitorização, como a medição de pressão cardíaca e pressão arterial, que no passado apenas podiam ser realizadas no hospital, podem ser realizadas hoje de forma contínua, usando sensores usáveis incorporados em *smartwatches*. A monitorização em tempo real assegurada por sistemas de saúde pode evitar hospitalizações não planeadas que resultam em custos de emergência elevados. A IoT oferece uma diversidade de vantagens para a conceção de sistemas de saúde, considerando redes de dispositivos conectados, aplicações e serviços *Cloud*, mas também pode facilitar o acesso confiável aos dados monitorizados. As aplicações IoT estão estreitamente relacionadas com os sistemas de saúde por meio de monitorização remota, casas inteligentes, dispositivos *wearable* e equipamentos médicos inteligentes. A IoT pode fornecer interoperabilidade ao domínio da saúde, além disso, inúmeras aplicações médicas foram desenvolvidas com base na IoT, o que demonstra as vantagens importantes dessa arquitetura para o desenvolvimento de sistemas de saúde eficientes e de baixo custo [36]. Para oferecer suporte a sistemas de saúde de alta qualidade, a IoT deve fornecer padronização, protocolos de comunicação sem fios eficientes, sensores melhorados bem como microprocessadores de baixo custo e de baixo consumo de energia [37].

Estes sistemas são necessários para melhorar o acesso global a informações médicas e de saúde. Estas inovações tecnológicas facilitam o acesso aos cuidados de saúde em populações envelhecidas e também fornecem novas oportunidades e métodos para processamento e avaliação de dados médicos [38]. Apesar de todas as vantagens dos sistemas de informação em saúde, uma questão complexa e importante associada à confidencialidade e segurança dos dados dos pacientes ainda não está resolvida [39],[40]. Os sistemas de saúde baseados na arquitetura IoT têm vários desafios principais, tais como, normalização, configuração de rede, modelo de negócio, QoS e segurança de dados [41].

É necessário garantir o acesso apropriado aos indivíduos corretos no momento certo e oferecer suporte a arquiteturas seguras. Vários desafios estão relacionados à segurança, privacidade e aspetos legais [42], [43]. Os sistemas de saúde baseados em IoT incorporam normalmente tecnologias de comunicação sem fio e a privacidade dos dados recolhidos deve ser protegida e fornecida apenas com autenticação. As pessoas permanecerão como parte essencial da arquitetura IoT que, consequentemente, afetará todas as características das suas vidas.

Os sistemas de saúde com base em IoT tem vários desafios de QoS tais como disponibilidade, confiabilidade, mobilidade, desempenho, escalabilidade e interoperabilidade [44]-[47]. As arquiteturas IoT são viáveis e significativas para a criação e desenvolvimento de sistemas de saúde. No entanto, vários desafios ainda continuam por resolver e é necessário continuar a investigar formas de resolver problemas de usabilidade, interface do utilizador, design onipresente e ergonomia, consulta e estrutura de dados, questões sociais e éticas, segurança e privacidade para a conceção de sistemas avançados de saúde.

Atualmente, a IoT é responsável por uma enorme quantidade de dados pessoais que são transferidos pela Internet sem a garantia da privacidade dos mesmos. Portanto, várias questões éticas e sociais podem ser invocadas. Este é um desafio importante a ser analisado particularmente nos sistemas de saúde da IoT, a fim de fornecer proteção contra o acesso a estes dados por fontes não autorizadas [48].

A implementação de sistemas de monitorização sobre o bem-estar do paciente e a sua rotina diária constitui informação muito sensível, portanto, os sistemas de saúde devem incorporar métodos de segurança fiáveis para garantir a confiabilidade dos dados. Legislação e regulamentação importante deve ser implementada com o objetivo de garantir os direitos do utilizador no desenvolvimento de sistemas de saúde baseados em IoT. O design destes sistemas deve considerar a ética como um fator importante, adotando políticas para garantir que são usadas infraestruturas seguras e confiáveis no seu desenvolvimento [49]. Os dados dos sistemas de saúde da IoT devem ser protegidos e implementar métodos de criptografia apropriada e medidas de segurança para evitar problemas de privacidade. Além disso, os dispositivos de IoT no contexto dos serviços de saúde devem ser regularmente verificados para não expor vulnerabilidades a ataques de segurança [50].

A proliferação de serviços de saúde levou a um aumento na quantidade de dados gerados, o que resulta em problemas de arquitetura no acesso e na estrutura de dados. Portanto, é necessário continuar a investigar novos métodos para resolver problemas relacionados com complexidade e diversidade dos dados gerados pelos sistemas de saúde. Além disso, a diversidade de fontes de dados requer um padrão uniforme de gestão de dados heterogêneos. A diversidade de conteúdo de dados requer uma interface de programação unificada para vários módulos de análise de dados, e a diversidade de dispositivos requer uma interface de plataforma uniforme de serviço padrão [51].

A principal aplicação dos sistemas de saúde personalizados é desenvolver sistemas inteligentes e omnipresentes para várias finalidades, como monitorização de saúde e bem-estar do paciente, reconhecimento de atividades e emoções, deteção de anomalias na rotina diária e supervisão de doenças específicas para ambientes de vida melhorados e melhoria da saúde ocupacional. Além disso, esses sistemas visam ser usados em larga escala, o que leva a uma proliferação de domínios de aplicações, incluindo o desenvolvimento de plataformas de partilha, visualização e análise de dados de assistência médica.

O desenvolvimento de sistemas de saúde está intimamente relacionado com o design e configuração de várias tecnologias de sensorização para aquisição de dados de forma eficiente e eficaz.

Os dispositivos móveis, como *smartphones*, *tablets* e *smartwatches*, são usados simultaneamente para a recolha de dados usando sensores embebidos, como GPS, câmara e microfone, mas também como uma ponte para a interface de dispositivos médicos externos. Além disso, os dispositivos móveis também são usados como unidades de processamento para transformar os dados recolhidos em conhecimento.

A conectividade é extremamente importante, pois é responsável por fazer a transmissão e partilha de dados entre os dispositivos de deteção e os restantes equipamentos. A maioria dos sistemas de saúde são baseados em tecnologias de comunicação sem fios [52]. Os protocolos Bluetooth e Zigbee são geralmente usados para comunicação de dispositivo para dispositivo, assim como tecnologias Wi-Fi e redes móveis, como 3G / 4G, que têm sido usadas recorrentemente para fornecer acesso à Internet [53].

O acesso aos dados monitorizados é fornecido usando várias abordagens. Por um lado, a maioria dos sistemas de saúde personalizados fornece acesso móvel aos dados recolhidos por meio de uma interface Web. Por outro lado, alguns sistemas de saúde não fornecem acesso remoto a dados. No entanto, há uma clara tendência para desenvolver sistemas que possam ser acedidos de forma ubíqua em qualquer lugar, a qualquer momento [54], [55].

A revisão do estado da arte sobre sistemas de saúde sugere a relevância de soluções de monitorização de pacientes em tempo real, além de incorporação de dispositivos móveis como unidades de processamento e sensorização. No entanto, existem também várias limitações, como consumo de energia, validação e calibração em cenários reais, modularidade, escalabilidade, e notificações mais eficazes e ubíquas que permitam atuar em tempo útil com o objetivo de melhorar as condições dos ambientes de vida e o bem-estar dos ocupantes [56], [57].

Proposta de métodos e arquiteturas IoT para ambientes de vida melhorados

Após a revisão do estado da arte sobre os diferentes conceitos envolvidos no desenvolvimento de soluções IoT com especial ênfase na área ligada à arquitetura de soluções para saúde foram propostas novos métodos e arquiteturas IoT para ambientes de vida melhorados e melhoria da saúde ocupacional.

1. Sistema baseado em IoT para monitorização de partículas em ambientes interiores

O método proposto tem por objetivo o desenvolvimento de uma arquitetura IoT para ambientes de vida melhorados através da monitorização em tempo real de PM. Este método utiliza um sensor PMS5003 de baixo custo que incorpora capacidade sensorial para medição do valor de partículas suspensas no ar com um diâmetro menor ou igual a 10 micrómetros ($\leq PM_{10}$), 2,5 micrómetros ($\leq PM_{2.5}$) e 1,0 micrómetros ($\leq PM_{1.0}$).

A PM pode ser definida como uma combinação multifacetada de partículas sólidas e liquidificadas de material biológico e mineral suspensas no ar e é, portanto, mencionada por vários investigadores como o poluente que afeta mais indivíduos [58], [59]. A PM inclui partículas, fumo e gotículas que são capazes de penetrar nas vias respiratórias dos seres humanos e podem causar efeitos negativos à saúde. A exposição à PM em ambientes interiores aumenta o risco de infeções respiratórias graves e mortalidade associada a crianças pequenas, mas também representa um importante fator de risco para doença cardiovascular, doença pulmonar obstrutiva crônica e cancro do pulmão na população adulta. Os efeitos da PM observados na saúde incluem aumento de problemas respiratórios, diminuição da função pulmonar, aumento das hospitalizações, doenças respiratórias e cardiovasculares, aumento da morbidade respiratória medida pelo absenteísmo no trabalho e aumento da mortalidade por doenças cardiopulmonares [60].

Em ambientes interiores, os efeitos na saúde das partículas biológicas inaladas podem ser significativos, uma vez que estes espaços possuem uma grande variedade de materiais biológicos. Um dos principais constituintes do fumo são partículas respiráveis. Estes são aerossóis com um diâmetro reduzido o suficiente para entrar e permanecer nos pulmões, muitos com diâmetro igual ou inferior a 6-7 micrómetros [29].

Consequentemente, o método proposto assume-se como uma relevante ferramenta avançada para exploração de dados e de apoio à decisão e ao diagnóstico médico que pode ser apoiado por dados históricos de exposição à PM no local onde o paciente vive. Este método centra-se na monitorização em tempo real das concentrações de partículas para melhorar a saúde ocupacional.

A arquitetura IoT proposta é composta por um protótipo de hardware para aquisição de dados ambiente e um portal Web desenvolvido em .NET para exploração de dados. O módulo de aquisição de dados é baseado em tecnologias de código aberto e recorre a tecnologia Wi-Fi para ligação à Internet, com várias vantagens em comparação com sistemas existentes, tais como modularidade, escalabilidade, baixo custo e fácil instalação. Os dados são armazenados numa base de dados SQL SERVER com recurso a serviços Web .NET. O módulo de aquisição de dados integra um microcontrolador WEMOS D1 com tecnologia de comunicação Wi-Fi integrada como unidade de comunicação e processamento e incorpora um sensor PMS5003 como unidade de sensorial.

A consulta de dados é realizada através de software Web desenvolvido em ASP.NET. Após a autenticação é possível aceder aos dados de exposição à PM. Os dados recolhidos podem ser consultados em formato tabela ou gráfico. Além disso, a Framework Web é responsável por guardar o histórico dos dados. O histórico dos dados de exposição à PM possibilita uma análise avançada de padrões da qualidade do ar. Esta Framework integra um gestor de alertas que envia notificações, via e-mail, quando um parâmetro específico excede a taxa máxima. Os dados recolhidos são analisados antes de serem inseridos na base de dados e no caso de excederem os limites parametrizados são enviadas notificações. Em resultado, é possível agir em tempo real, o que conduz à conceção de ambientes de vida melhorados. O método proposto é confiável e de baixo custo e pode ser facilmente configurado e instalado pelo utilizador final.

Em comparação com outros métodos do estado da arte, a arquitetura proposta fornece uma plataforma Web para consulta de dados e notificações sendo relevante para apoiar o planeamento de intervenções no edifício e incluí partilha de dados com a equipa médica. Tendo em conta que tipicamente ocupamos cerca de 90% do tempo em ambientes interiores, é necessário monitorizar o nível de PM para o planeamento de mudanças de hábitos e até mesmo intervenções na ventilação para a conceção de ambientes de vida melhorados. Este sistema faz uma contribuição significativa em comparação com os sistemas existentes de monitorização da qualidade do ar devido ao seu baixo custo de construção, facilidade de instalação, modularidade, escalabilidade e fácil acesso aos dados de monitorização em tempo real através da Web.

Em contraste com a maioria das soluções de disponíveis no estado da arte que têm de ser instaladas por profissionais especializados, a arquitetura proposta pode ser configurada e instalada pelo utilizador final. Esta arquitetura permite a escalabilidade do sistema, proporcionando flexibilidade e capacidade de expansão, já que o espaço pode começar a ser monitorizado com apenas um módulo de aquisição de dados e outros módulos podem ser adicionados conforme as necessidades e a complexidade do espaço em particular.

Os resultados dos testes revelam que o método proposto fornece uma avaliação eficaz do PM e evita o risco de exposição. De facto, os níveis de PM podem ser extremamente diferentes dos que são considerados saudáveis. Portanto, a arquitetura proposta é uma ferramenta útil para monitorizar os níveis de PM e garantir a sua categorização. Os resultados permitem também concluir que os ocupantes só se apercebem das más condições da qualidade do ar em situações extremas, por isso, com recurso a este novo método, é possível detetar e corrigir os problemas em tempo útil.

2. Avaliação da qualidade do ar interior com recurso a um sistema de monitorização de CO_2 baseado na Internet das Coisas

O método proposto apresenta uma arquitetura IoT para monitorização de CO_2 em tempo real para ambientes de vida melhorados. De forma a desenvolver um método de baixo custo, apenas um parâmetro da qualidade do ar interior é monitorizado. O CO_2 foi selecionado, pois é fácil de medir e pode ser usado como um indicador de outros poluentes e, portanto, da qualidade do ar em geral.

A arquitetura proposta é composta por um modulo de aquisição de dados e software para Web e móvel para consulta de dados. Esta arquitetura é baseada em tecnologias de código aberto com várias vantagens em comparação aos sistemas existentes, como modularidade, escalabilidade, baixo custo e fácil instalação. Os dados recolhidos são armazenados numa base de dados. O módulo de aquisição de dados incorpora um microcontrolador ESP8266 com tecnologia de comunicação Wi-Fi integrada como unidade de comunicação e processamento e um sensor de CO_2 como unidade de sensorial. O método proposto incorpora ligação à rede de Internet sem fios usando o módulo ESP8266 que implementa o protocolo de rede IEEE 802.11 b/g/n.

Diversos estudos associam concentrações elevadas de CO_2 com défice de desempenho no trabalho e aumento de sintomas e problemas de saúde. Os níveis excessivos de CO_2 em ambientes interiores é um problema conhecido e estudado há vários anos [61]–[65]. Existe uma correlação evidente entre níveis elevados de CO_2 e altas concentrações de outros poluentes em ambientes interiores [66]. Assim sendo, é necessário um método eficaz para monitorizar o CO_2

e fornecer notificações em tempo real para melhorar a saúde ocupacional e proporcionar um ambiente de vida seguro e saudável.

Através da implementação de monitorização em tempo real e disponibilidade de dados com recurso a ferramentas avançadas é possível detetar e interferir de forma assertiva em situações de risco para ambientes de vida melhorados. Desta forma o método proposto é uma ferramenta útil para a criação de ambientes de vida melhorados e de cidades inteligentes. Os benefícios para a saúde, conforto e produtividade associados a boas condições de qualidade do ar podem ser atingidos através da diminuição da concentração de poluentes enquanto a ventilação permanece inalterada [67].

Considerando o impacto das condições ambiente na saúde é proposto um método confiável e de baixo custo que pode ser facilmente configurado e instalado para ambientes de vida melhorados. Os dados recolhidos são armazenados numa base de dados SQL SERVER com recurso a serviços Web .NET. A Framework Web e os serviços Web .NET estão instalados na mesma instância do Windows Server. Os Serviços Web .NET são usados para transmissão dos dados recolhidos e para partilha de dados com a aplicação móvel. A Framework Web está diretamente conectada à base de dados usando autenticação SQL Server.

A arquitetura proposta incorpora um software móvel que permite não só a consulta dos últimos dados recolhidos e receber notificações em tempo real, mas também configurar os níveis de CO_2 para o envio de alertas. O acesso aos dados requer autenticação. Esta aplicação móvel fornece não apenas acesso fácil aos dados da qualidade do ar em tempo real, mas também permite o acesso ao histórico e gráficos para visualização. O método proposto permite uma análise precisa e detalhada do comportamento da qualidade do ar. O software Web permite também ter uma referência geográfica do local onde os dados foram recolhidos.

Os resultados mostram que, sob certas condições, os valores de qualidade do ar são significativamente menores do que aqueles considerados saudáveis. Os testes realizados revelam a capacidade do sistema de analisar a qualidade do ar em tempo real, o potencial de planear intervenções para garantir condições seguras, saudáveis e confortáveis, mas também identificar múltiplas situações ou hábitos que afetam negativamente a qualidade do ar.

Este método incorpora tecnologias de comunicação sem fios e computação móvel que fornecem o acesso fácil e rápido aos dados recolhidos, mas permite também uma análise precisa da evolução temporal da qualidade do ar interior. Assim, o método proposto é uma ferramenta poderosa para apoiar a tomada de decisões sobre possíveis intervenções para ambientes de vida melhorados.

Numerosas evidências científicas mostram que o CO_2 é o gás de efeito estufa mais relevante para o clima na atmosfera da Terra. Altas concentrações de CO_2 no ambiente exterior levam naturalmente a maiores concentrações em ambientes interiores devido à contribuição de fontes internas (metabolismo humano e equipamento de combustão) [68],[69]. É necessário controlar a concentração de CO_2 de maneira efetiva, o que exige uma monitorização em tempo-real.

O método proposto incorpora um sistema de gestão de alertas que envia notificações quando o ambiente interior apresenta deficiências. Com base nos valores da literatura, os valores máximos e mínimos da concentração CO_2 são pré-definidos pelo sistema. Contudo, a arquitetura proposta permite que esses valores sejam modificados para fins específicos. Quando um valor excede o limite definido, o utilizador é notificado em tempo real por e-mail, SMS ou notificação remota via *smartphone*. Os resultados permitem aferir que as notificações remotas oferecem várias vantagens quando o objetivo é conseguir mudanças efetivas para ambientes de vida melhorados. Por um lado, as mensagens de notificação promovem mudanças de comportamento. As mensagens de notificação permitem uma ação em tempo útil para a melhoria da saúde ocupacional. Por outro lado, os alertas em tempo real permitem a identificação de padrões de situações de qualidade ambiente deficiente e o planeamento de intervenções para ambientes de vida melhorados.

Quando comparado com outros sistemas o método proposto apresenta várias vantagens tais como a facilidade de instalação e configuração, mas também devido à reduzida dimensão do módulo de aquisição de dados (5,5 cm × 2,5 cm × 2,5 cm de profundidade). Os dados recolhidos podem ser partilhados com equipas médicas para suporte ao diagnóstico. Tendo em conta a importância da qualidade do ar interior para a saúde dos ocupantes, mas também o tempo que é ocupado em ambientes interiores é necessário monitorizar os níveis de CO_2 com vista à mudança de hábitos para ambientes de vida melhorados. Este sistema faz uma contribuição significativa em comparação com os sistemas existentes de monitorização da qualidade do ar devido ao seu baixo custo de construção, instalação, modularidade, escalabilidade e fácil acesso a dados em tempo real através da Framework Web e móvel.

3. Solução de baixo custo para supervisão de qualidade do ar para ambientes de vida melhorados através da Internet das Coisas

Esta secção apresenta uma arquitetura IoT para monitorização de qualidade do ar composta por um modulo de aquisição de dados e software Web e aplicação móvel para consulta dos dados. O módulo de aquisição de dados é desenvolvido com recuso ao microcontrolador ESP8266 que executa funções de processamento e comunicação. O sensor MICS-6814 é utilizado como unidade sensorial. Os dados recolhidos são enviados para o *ThingSpeak*, uma plataforma *Cloud* de código aberto que disponibiliza uma API para armazenamento e consulta de dados. A arquitetura proposta permite que os dados sejam consultados de forma a detetar condições deficientes em tempo real e planear intervenções para ambientes de vida melhorados. Estes dados podem ser consultados por médicos para apoiar diagnósticos e correlacionar os sintomas e problemas de saúde dos pacientes com as condições ambiente em que vivem.

O método proposto é capaz de recolher dados de vários parâmetros de qualidade do ar, como NH_3 (amoníaco), CO (monóxido de carbono), NO_2 (dióxido de azoto), C_3H_8 (propano), C_4H_{10} (butano), CH_4 (metano), H_2 (hidrogénio) e C_2H_5OH (etanol). O controlo das concentrações destes parâmetros é extremamente importante para proporcionar ambientes de vida melhorados.

O método proposto pode ser dividido em duas partes: uma unidade de processamento e comunicação e uma unidade de deteção. Este sistema é construído usando o ESP8266 como um microcontrolador e usando o recurso de comunicação Wi-Fi integrada para conexão à Internet. A unidade sensorial incorpora um sensor MICS-6814 que é capaz de medir vários poluentes.

As soluções de monitorização da qualidade do ar para edifícios residenciais e / ou comerciais são caras e baseiam-se em amostragem aleatória. No entanto, esses procedimentos são limitados, fornecendo apenas dados relacionadas a uma amostragem específica e sendo desprovidos de informação espácio-temporal. Algumas dessas soluções oferecem portabilidade e são compactas, oferecendo registo de dados no próprio equipamento, mas não permitem a disponibilidade de dados em tempo real para gestores de edifícios de forma a possibilitar uma intervenção rápida e eficiente para melhorar a saúde ocupacional. As soluções disponíveis no mercado são caras e não oferecem compatibilidade móvel para consulta de dados e notificações em tempo real. Estas soluções permitem apenas um histórico de dados limitado à memória do dispositivo e exige procedimentos de download e manipulação de dados com software específico.

A arquitetura proposta visa desenvolver um sistema de monitorização com tecnologia integrada, combinando sensibilidade, flexibilidade e precisão de medição em tempo real, permitindo uma evolução significativa dos atuais sistemas de supervisão da qualidade do ar. Esta arquitetura fornece acesso fácil, intuitivo e rápido aos dados de qualidade do ar, bem como notificações essenciais no caso de situação de qualidade do ar deficiente para fornecer intervenção em tempo real e melhorar a saúde ocupacional. A supervisão e análise de qualidade do ar em tempo real não deve apenas ser considerada como uma ferramenta de tomada de decisão relevante para planear mudanças de comportamento para melhorar a saúde ocupacional, mas também para deteção de condições ambientais deficientes em tempo real. Os resultados obtidos são promissores, representando uma contribuição significativa para os sistemas de monitorização de qualidade do ar. A arquitetura proposta é capaz de assegurar uma correta monitorização de um diverso número de tipos de gases. Os testes mostram a capacidade do método proposto para proporcionar ambientes de vida melhorados e promover a saúde ocupacional.

Principais Conclusões

AAL e a IoT assumem um papel fundamental para resolver os problemas de independência da população, em geral, e de indivíduos debilitados, em particular. Casas inteligentes, *smartphones*, tecnologias *wearable* e a IoT podem em conjunto criar sistemas AAL que oferecem diversas oportunidades para resolver problemas relacionados emergências, deficiências e doenças. Apesar dos benefícios e avanços tecnológicos dos sistemas AAL, o cuidado humano nunca deve ser substituído, porque as relações e interações sociais são fundamentais. A IoT e AAL continuarão a contribuir lado a lado para alcançar avanços científicos no campo da vida assistida, permitindo também a redução do custo destes sistemas. Apesar de todas as vantagens no uso de arquiteturas IoT, muitos problemas continuam em aberto, tais como escalabilidade, problemas de qualidade de serviço e segurança e privacidade.

O principal foco desta Tese é o desenvolvimento de novos métodos e arquiteturas IoT para monitorização de ambientes de vida melhorados que sejam de baixo custo, fácil instalação, modulares e escaláveis com recurso a tecnologias de comunicação sem fios e computação móvel. Os *smartphones* são parte integrante da rotina diária dos países desenvolvidos. Os EUA tiveram um crescimento exponencial no uso do *smartphone*. Na verdade, o uso de dispositivos móveis por adultos estava em 33% em 2011, 56% no final de 2013 e 64% no início de 2015 [70]. Na Holanda, 70% da população total e 90% dos adolescentes possuem um *smartphone* [71]; na Alemanha, 40% das pessoas usam *smartphones* [72] e, no Reino Unido (Reino Unido), 51% dos adultos possuem *smartphones* [73]. Os *smartphones* incorporam excelentes recursos de processamento, armazenamento e sensorização podendo ser usados para fornecer acesso aos dados de monitorização. Pelo que os métodos propostos têm suporte para dispositivos móveis para consulta de dados em formato numérico e gráfico e em tempo real.

A Tese tem como principal objetivo a definição e desenvolvimento de arquiteturas IoT, modulares e escaláveis para monitorização da qualidade do ar para ambientes de vida melhorados. Esta arquitetura incorpora vários conceitos desde aquisição, processamento, armazenamento, análise e visualização de dados. O sistema proposto incorpora também uma Framework de gestão de alertas que notifica o utilizador em tempo real e de forma ubíqua quando a qualidade do ar interior deficiente. O método proposto suporta vários métodos de notificação, como notificações remotas para *smartphone*, SMS e e-*mail*. Este mecanismo de notificações em tempo real oferece várias vantagens quando o objetivo é alcançar mudanças efetivas para ambientes de vida melhorados. O método desenvolvido recorre a sensores confiáveis de baixo custo de forma possibilitar a sua implementação em alta escala. O mesmo deve incorporar ferramentas avançadas de exploração de dados e permitir o acesso aos dados de forma ubíqua em qualquer lugar e a qualquer momento.

O objetivo principal foi dividido em 4 objetivos intermédios que começaram pela revisão do estado da arte. Esta revisão teve por objetivo compreender e avaliar corretamente o paradigma IoT nomeadamente a nível das diversas oportunidades para múltiplas aplicações, particularmente sistemas de saúde. A revisão do estado da arte conduziu ao desenho e conceção de uma arquitetura IoT para monitorização de PM que incorpora uma Framework Web para consulta e histórico de dados e notificações, apresentada no capítulo 3 da Tese. Como terceiro objetivo intermédio, foi realizado o desenvolvimento de uma Framework para a avaliação da qualidade do ar com recurso a supervisão de dióxido de carbono. Esta Framework é composta por um sistema de monitorização, software Web e aplicação móvel para acesso aos dados e suporta vários tipos de alertas como por exemplo, SMS, e-mail e notificações remotas através da aplicação móvel, e é descrita no capítulo 4. No capítulo 5, é proposta uma arquitetura IoT para supervisão de vários parâmetros da qualidade do ar em que os dados são armazenados na *Cloud*. Esta *framework* combina sensibilidade, flexibilidade e precisão de medição em tempo real, permitindo uma evolução significativa dos atuais sistemas de monitorização da qualidade do ar. Os resultados mostram que este sistema fornece acesso fácil, intuitivo e rápido aos dados de qualidade do ar bem como notificações essenciais em situações de qualidade do ar deficiente para fornecer intervenção em tempo real para ambientes de vida melhorados.

O objetivo principal desta Tese foi atingido com o desenvolvimento de novas arquiteturas e IoT para monitorização da qualidade do ar e ambientes de vida melhorados. Estas arquiteturas apresentam novos métodos eficientes, de baixo custo, escaláveis e modulares que suportam tecnologias móveis para notificações, visualização e análise de dados contribuindo efetivamente para ambientes de vida melhorados e para a melhoria da saúde ocupacional.

Direções para trabalho futuro

As novas arquiteturas IoT para ambientes de vida melhorados propostas permitem definir sistemas de monitorização modulares e escaláveis e incorporaram vários conceitos desde aquisição, processamento, armazenamento, análise e visualização de dados. O acesso a estes dados e as notificações em tempo real permitem a identificação de padrões de eventos não saudáveis recorrentes e possibilitam a implementação de medidas para evitar que estes ocorram. Para além disso, estes dados podem ser partilhados com equipas médicas para suporte ao diagnóstico.

No entanto, as arquiteturas propostas têm limitações sendo que precisam de maior validação experimental para melhorar a sua precisão e calibração. Além disso, melhorias a nível de hardware e software também estão planeadas para adaptar o sistema a casos ou problemas específicos, como a supervisão de salas de aula, residências para idosos e hospitais.

No futuro, as arquiteturas propostas vão ser melhoradas através do desenvolvimento de métodos seguros para partilha de informações com profissionais de saúde de forma a apoiar o diagnóstico. Os dados da qualidade do ar podem ser extremamente úteis para fornecer suporte para análises clínicas por profissionais de saúde. Ao monitorizar a qualidade do ambiente, podemos detetar situações não saudáveis em tempo real causadas, por exemplo, por sistemas de ventilação inadequados ou planos de intervenção desapropriados. No futuro soluções como as propostas nesta Tese vão fazer parte integrante da nossa rotina diária com o objetivo de fornecer acesso ubíquo aos dados de monitorização para ambientes de vida melhorados.

Referências

[1] D. Giusto, A. Iera, G. Morabito, and L. Atzori, Eds., The Internet of Things. New York, NY: Springer New York, 2010.

[2] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, “Internet of Things (IoT): A vision, architectural elements, and future directions,” Future Generation Computer Systems, vol. 29, no. 7, pp. 1645–1660, Sep. 2013.

[3] R. Khan, S. U. Khan, R. Zaheer, and S. Khan, “Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges,” in 2012 10th International Conference on Frontiers of Information Technology, Islamabad, Pakistan, 2012, pp. 257–260.

[4] J. Jara, M.A. Zamora and A. Skarmeta, “Glowbal IP: An adaptive and transparent IPv6 integration in the Internet of Things,” Mobile Information Systems, no. 3, pp. 177–197, 2012.

[5] J. Jermyn, R. P. Jover, I. Murynets, M. Istomin, and S. Stolfo, “Scalability of Machine to Machine systems and the Internet of Things on LTE mobile networks,” in 2015 IEEE 16th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM), Boston, MA, USA, 2015, pp. 1–9.

[6] D. De Guglielmo, G. Anastasi, and A. Seghetti, “From IEEE 802.15.4 to IEEE 802.15.4e: A Step Towards the Internet of Things,” in Advances onto the Internet of Things, vol. 260, S. Gaglio and G. Lo Re, Eds. Cham: Springer International Publishing, 2014, pp. 135–152.

[7] R. Falk, F. Kohlmayer, and A. Köpf, Device and method for providing RFID identification data for an authentication server. Google Patents, 2015.

[8] K. Curran, A. Millar, and C. Mc Garvey, “Near Field Communication,” International Journal of Electrical and Computer Engineering (IJECE), vol. 2, no. 3, Apr. 2012.

[9] C. Gomez, J. Oller, and J. Paradells, “Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology,” Sensors, vol. 12, no. 9, pp. 11734–11753, Aug. 2012.

[10] I. J. Garcia Zuazola, L. Bengtsson, A. Perallos, and H. Landaluce, “Simplified computation in memoryless anti-collision RFID identification protocols,” Electronics Letters, vol. 50, no. 17, pp. 1250–1252, Aug. 2014.

[11] S. Raza, P. Misra, Z. He, and T. Voigt, “Bluetooth smart: An enabling technology for the Internet of Things,” in 2015 IEEE 11th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Abu Dhabi, United Arab Emirates, 2015, pp. 155–162.

[12] C. Doukas, Building internet of things with the Arduino: V1.1 [Arduino V.10 ready! ; covers: communication with wired and wireless networks, android communication, cloud communication and more!]. S.l.: CreateSpace, 2012.

[13] M. C. Ramon, “Intel Galileo and Intel Galileo Gen 2,” in Intel® Galileo and Intel® Galileo Gen 2, Berkeley, CA: Apress, 2014, pp. 1–33.

[14] E. Upton and G. Halfacree, Raspberry Pi user guide, 4th edition. Chichester: Wiley, 2016.

[15] P. Raspaile and V. Keswani, “Integrating Wireless Sensor Network with Open Source Cloud for application of Smart Home,” International Journal of Engineering Science & Advanced Technology, vol. 5, no. 4, pp. 425–428, 2015.

[16] M. Gigli and S. Koo, “Internet of Things: Services and Applications Categorization,” Advances in Internet of Things, vol. 01, no. 02, pp. 27–31, 2011.

[17] D. L. McGuinness and F. Van Harmelen, “OWL web ontology language overview,” W3C recommendation, vol. 10, no. 10, p. 2004, 2004.

[18] D. Peintner, H. Kosch, and J. Heuer, “Efficient XML Interchange for rich internet applications,” in 2009 IEEE International Conference on Multimedia and Expo, 2009, pp. 149–152.

[19] “Universal Open Platform and Reference Specification for Ambient Assisted Living: http://www.universaal.org/.”.

[20] P. Koleva, K. Tonchev, G. Balabanov, A. Manolova, and V. Poulkov, "Challenges in designing and implementation of an effective Ambient Assisted Living system," in Telecommunication in Modern Satellite, Cable and Broadcasting Services (TELSIKS), 2015 12th International Conference on, 2015, pp. 305–308.

[21] A. Caragliu, C. Del Bo, and P. Nijkamp, "Smart Cities in Europe," Journal of Urban Technology, vol. 18, no. 2, pp. 65–82, Apr. 2011.

[22] H. Schaffers, N. Komninos, M. Pallot, B. Trousse, M. Nilsson, and A. Oliveira, "Smart Cities and the Future Internet: Towards Cooperation Frameworks for Open Innovation," in The Future Internet, vol. 6656, J. Domingue, A. Galis, A. Gavras, T. Zahariadis, D. Lambert, F. Cleary, P. Daras, S. Krco, H. Müller, M.-S. Li, H. Schaffers, V. Lotz, F. Alvarez, B. Stiller, S. Karnouskos, S. Avessta, and M. Nilsson, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 431–446.

[23] H. Chourabi et al., "Understanding Smart Cities: An Integrative Framework," 2012 45th Hawaii international conference on system sciences. IEEE, 2012, pp. 2289–2297.

[24] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," IEEE Internet of Things Journal, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[25] M. Batty et al., "Smart cities of the future," The European Physical Journal Special Topics, vol. 214, no. 1, pp. 481–518, Nov. 2012.

[26] J. M. Hernández-Muñoz et al., "Smart Cities at the Forefront of the Future Internet," in The Future Internet, vol. 6656, J. Domingue, A. Galis, A. Gavras, T. Zahariadis, D. Lambert, F. Cleary, P. Daras, S. Krco, H. Müller, M.-S. Li, H. Schaffers, V. Lotz, F. Alvarez, B. Stiller, S. Karnouskos, S. Avessta, and M. Nilsson, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 447–462.

[27] J. M. Seguel, R. Merrill, D. Seguel, and A. C. Campagna, "Indoor Air Quality," American Journal of Lifestyle Medicine, vol. 11, no. 4, pp. 284–2895, 2016.

[28] N. Bruce, R. Perez-Padilla, and R. Albalak, "Indoor air pollution in developing countries: a major environmental and public health challenge," Bulletin of the World Health Organization, vol. 78, no. 9, pp. 1078–1092, 2000.

[29] A. P. Jones, "Indoor air quality and health," Atmospheric Environment, vol. 33, no. 28, pp. 4535–4564, Dec. 1999.

[30] S. Al-Janabi, I. Al-Shourbaji, M. Shojafar, and S. Shamshirband, “Survey of main challenges (security and privacy) in wireless body area networks for healthcare applications,” Egyptian Informatics Journal, vol. 18, no. 2, pp. 113–122, Jul. 2017.

[31] I. Azimi, A. M. Rahmani, P. Liljeberg, and H. Tenhunen, “Internet of things for remote elderly monitoring: a study from user-centered perspective,” Journal of Ambient Intelligence and Humanized Computing, Jun. 2016.

[32] E. Tenner and J. E. Rall, Why things bite back: Technology and the revenge of unintended consequences. Vintage Books New York, 1997.

[33] United Nations, New York, Ny. Department of Economic and Social Affairs. World population ageing, 1950-2050. United Nations Publications, 2002.

[34] Rk. Kumar, “Technology and healthcare costs,” Annals of Pediatric Cardiology, vol. 4, no. 1, p. 84, 2011.

[35] “Centers for Disease Control and Prevention, ‘The state of aging and health in America 2007,’ N. A. on an Aging Society, 2007, Available: https://www.cdc.gov/aging/pdf/saha_2007.pdf.” .

[36] F. Ullah, M. A. Habib, M. Farhan, S. Khalid, M. Y. Durrani, and S. Jabbar, “Semantic interoperability for big-data in heterogeneous IoT infrastructure for healthcare,” Sustainable Cities and Society, vol. 34, pp. 90–96, Oct. 2017.

[37] F. Fernandez and G. C. Pallis, “Opportunities and challenges of the Internet of Things for healthcare: Systems engineering perspective,” in Wireless Mobile Communication and Healthcare (Mobihealth), 2014 EAI 4th International Conference on, 2014, pp. 263–266.

[38] R. Haux, “Health information systems - past, present, future,” Int J Med Inform, vol. 75, no. 3–4, pp. 268–281, Apr. 2006.

[39] D. Chen and H. Zhao, “Data Security and Privacy Protection Issues in Cloud Computing,” International Conference on Computer Science and Electronics Engineering. Vol. 1. IEEE 2012, pp. 647–651.

[40] A. Appari and M. E. Johnson, “Information security and privacy in healthcare: current state of research,” International journal of Internet and enterprise management, vol. 6, no. 4, pp. 279–314, 2010.

[41] S. M. Riazul Islam, Daehan Kwak, M. Humaun Kabir, M. Hossain, and Kyung-Sup Kwak, “The Internet of Things for Health Care: A Comprehensive Survey,” IEEE Access, vol. 3, pp. 678–708, 2015.

[42] A. Roy, C. Roy, S. Misra, Y. Rahulamathavan, and M. Rajarajan, “CARE: Criticality-Aware Data Transmission in CPS-Based Healthcare Systems,” in 2018 IEEE International Conference on Communications Workshops (ICC Workshops), Kansas City, MO, USA, 2018, pp. 1–6.

[43] Y. Rahulamathavan, R. C.-W. Phan, M. Rajarajan, S. Misra, and A. Kondoz, “Privacy-preserving blockchain based IoT ecosystem using attribute-based encryption,” in 2017 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), Bhubaneswar, 2017, pp. 1–6.

[44] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, “Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications,” IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2347–2376, 2015.

[45] L. Atzori, A. Iera, and G. Morabito, “The Internet of Things: A survey,” Computer Networks, vol. 54, no. 15, pp. 2787–2805, Oct. 2010.

[46] D. Miorandi, S. Sicari, F. De Pellegrini, and I. Chlamtac, “Internet of things: Vision, applications and research challenges,” Ad Hoc Networks, vol. 10, no. 7, pp. 1497–1516, Sep. 2012.

[47] R. Khan, S. U. Khan, R. Zaheer, and S. Khan, “Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges,” 2012, pp. 257–260.

[48] L. Royakkers, J. Timmer, L. Kool, and R. van Est, “Societal and ethical issues of digitization,” Ethics and Information Technology, vol. 20, no. 2, pp. 127–142, Jun. 2018.

[49] A. Shahraki and O. Haugen, “Social ethics in Internet of Things: An outline and review,” in 2018 IEEE Industrial Cyber-Physical Systems (ICPS), St. Petersburg, 2018, pp. 509–516.

[50] A. Iyengar, A. Kundu, and G. Pallis, “Healthcare Informatics and Privacy,” IEEE Internet Computing, vol. 22, no. 2, pp. 29–31, Mar. 2018.

[51] X. Ma, Z. Wang, S. Zhou, H. Wen, and Y. Zhang, “Intelligent Healthcare Systems Assisted by Data Analytics and Mobile Computing,” Wireless Communications and Mobile Computing, vol. 2018, pp. 1–16, Jul. 2018.

[52] I. Ganchev, N. M. Garcia, C. Dobre, C. X. Mavromoustakis, and R. Goleva, Eds., Enhanced Living Environments: Algorithms, Architectures, Platforms, and Systems, vol. 11369. Cham: Springer International Publishing, 2019.

[53] C. X. Mavromoustakis, N. M. Garcia, R. I. Goleva, G. Mastorakis, and C. Dobre, Eds., Ambient assisted living and enhanced living environments: principles, technologies and control. Amsterdam ; Boston: Butterworth-Heinemann, 2017.

[54] P. Nuno, A. Pedro, V. Joaquim, and da C. M. Dias, "Evaluation of a ubiquitous and interoperable computerised system for remote monitoring of ambulatory post-operative pain: A randomised controlled trial," Technology and Health Care, no. 1, pp. 63–75, 2014.

[55] N. Pombo and N. M. Garcia, "ubiSleep: An ubiquitous sensor system for sleep monitoring," in 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), New York, NY, 2016, pp. 1–4.

[56] G. Marques, N. Garcia, and N. Pombo, "A Survey on IoT: Architectures, Elements, Applications, QoS, Platforms and Security Concepts," in Advances in Mobile Cloud Computing and Big Data in the 5G Era, vol. 22, C. X. Mavromoustakis, G. Mastorakis, and C. Dobre, Eds. Cham: Springer International Publishing, 2017, pp. 115–130.

[57] I. M. Pires, N. M. Garcia, N. Pombo, F. Flórez-Revuelta, and N. D. Rodríguez, "Validation Techniques for Sensor Data in Mobile Health Applications," Journal of Sensors, vol. 2016, pp. 1–9, 2016.

[58] M. Kampa and E. Castanas, "Human health effects of air pollution," Environmental Pollution, vol. 151, no. 2, pp. 362–367, Jan. 2008.

[59] M. J. Utell and M. W. Frampton, "Acute Health Effects of Ambient Air Pollution: The Ultrafine Particle Hypothesis," Journal of Aerosol Medicine, vol. 13, no. 4, pp. 355–359, Jan. 2000.

[60] K. Nishihara and K. Mori, "Relationships between epinephrine, waking time, and self-estimates for naps at night," Physiol. Behav., vol. 52, no. 2, pp. 397–400, Aug. 1992.

[61] S. Bhattacharya, S. Sridevi, and R. Pitchiah, "Indoor air quality monitoring using wireless sensor network," 2012, pp. 422–427.

[62] S. C. Lee and M. Chang, "Indoor and outdoor air quality investigation at schools in Hong Kong," Chemosphere, vol. 41, no. 1–2, pp. 109–113, Jul. 2000.

[63] O. A. Seppanen, W. J. Fisk, and M. J. Mendell, “Association of Ventilation Rates and CO2 Concentrations with Health andOther Responses in Commercial and Institutional Buildings,” Indoor Air, vol. 9, no. 4, pp. 226–252, Dec. 1999.

[64] G. Ramachandran et al., “Indoor Air Quality in Two Urban Elementary Schools—Measurements of Airborne Fungi, Carpet Allergens, CO 2 , Temperature, and Relative Humidity,” Journal of Occupational and Environmental Hygiene, vol. 2, no. 11, pp. 553–566, Nov. 2005.

[65] P. A. Scheff, V. K. Paulius, S. W. Huang, and L. M. Conroy, “Indoor Air Quality in a Middle School, Part I: Use of CO 2 as a Tracer for Effective Ventilation,” Applied Occupational and Environmental Hygiene, vol. 15, no. 11, pp. 824–834, Jan. 2000.

[66] U. Satish et al., “Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance,” Environmental Health Perspectives, Sep. 2012.

[67] P. Wargocki, D. P. Wyon, J. Sundell, G. Clausen, and P. O. Fanger, “The Effects of Outdoor Air Supply Rate in an Office on Perceived Air Quality, Sick Building Syndrome (SBS) Symptoms and Productivity,” Indoor Air, vol. 10, no. 4, pp. 222–236, Dec. 2000.

[68] A. A. Lacis, G. A. Schmidt, D. Rind, and R. A. Ruedy, “Atmospheric CO2: Principal Control Knob Governing Earth’s Temperature,” Science, vol. 330, no. 6002, pp. 356–359, Oct. 2010.

[69] H. B. Awbi, Ventilation of buildings. Taylor & Francis, 2003.

[70] H. Müller, J. L. Gove, J. S. Webb, and A. Cheang, “Understanding and Comparing Smartphone and Tablet Use: Insights from a Large-Scale Diary Study,” in Proceedings of the Annual Meeting of the Australian Special Interest Group for Computer Human Interaction, 2015, pp. 427–436.

[71] A. J. A. M. van Deursen, C. L. Bolle, S. M. Hegner, and P. A. M. Kommers, “Modeling habitual and addictive smartphone behavior,” Computers in Human Behavior, vol. 45, pp. 411–420, Apr. 2015.

[72] C. Montag et al., “Smartphone usage in the 21st century: who is active on WhatsApp?,” BMC Research Notes, vol. 8, no. 1, Dec. 2015.

[73] C. Pearson and Z. Hussain, “Smartphone Use, Addiction, Narcissism, and Personality:: A Mixed Methods Investigation,” International Journal of Cyber Behavior, Psychology and Learning, vol. 5, no. 1, pp. 17–32, 2015.

Abstract

Ambient Assisted Living (AAL) is an emerging multidisciplinary research area that aims to create an ecosystem of different types of sensors, computers, mobile devices, wireless networks, and software applications for enhanced living environments and occupational health. There are several challenges in the development and implementation of an effective AAL system, such as system architecture, human-computer interaction, ergonomics, usability, and accessibility. There are also social and ethical challenges, such as acceptance by seniors and the privacy and confidentiality that must be a requirement of AAL devices. It is also essential to ensure that technology does not replace human care and is used as a relevant complement.

The Internet of Things (IoT) is a paradigm where objects are connected to the Internet and support sensing capabilities. IoT devices should be ubiquitous, recognize the context, and support intelligence capabilities closely related to AAL. Technological advances allow defining new advanced tools and platforms for real-time health monitoring and decision making in the treatment of various diseases. IoT is a suitable approach to building healthcare systems, and it provides a suitable platform for ubiquitous health services, using, for example, portable sensors to carry data to servers and smartphones for communication. Despite the potential of the IoT paradigm and technologies for healthcare systems, several challenges to be overcome still exist. The direction and impact of IoT in the economy are not clearly defined, and there are barriers to the immediate and ubiquitous adoption of IoT products, services, and solutions.

Several sources of pollutants have a high impact on indoor living environments. Consequently, indoor air quality is recognized as a fundamental variable to be controlled for enhanced health and well-being. It is critical to note that typically most people occupy more than 90% of their time inside buildings, and poor indoor air quality negatively affects performance and productivity.

Research initiatives are required to address air quality issues to adopt legislation and real-time inspection mechanisms to improve public health, not only to monitor public places, schools, and hospitals but also to increase the rigor of building rules. Therefore, it is necessary to use real-time monitoring systems for correct analysis of indoor air quality to ensure a healthy environment in at least public spaces. In most cases, simple interventions provided by homeowners can produce substantial positive impacts on indoor air quality, such as avoiding indoor smoking and the correct use of natural ventilation.

An indoor air quality monitoring system helps the detection and improvement of air quality conditions. Local and distributed assessment of chemical concentrations is significant for safety

(*e.g.*, detection of gas leaks and monitoring of pollutants) as well as to control heating, ventilation, and HVAC systems to improve energy efficiency. Real-time indoor air quality monitoring provides reliable data for the correct control of building automation systems and should be assumed as a decision support platform on planning interventions for enhanced living environments. However, the monitoring systems currently available are expensive and only allow the collection of random samples that are not provided with time information. Most solutions on the market only allow data consulting limited to device memory and require procedures for downloading and manipulating data with specific software. In this way, the development of innovative environmental monitoring systems based on ubiquitous technologies that allow real-time analysis becomes essential.

This thesis resulted in the design and development of IoT architectures using modular and scalable structures for air quality monitoring based on data collected from cost-effective sensors for enhanced living environments. The proposed architectures address several concepts, including acquisition, processing, storage, analysis, and visualization of data. These systems incorporate an alert management Framework that notifies the user in real-time in poor indoor air quality scenarios. The software Framework supports multiple alert methods, such as push notifications, SMS, and e-mail. The real-time notification system offers several advantages when the goal is to achieve effective changes for enhanced living environments. On the one hand, notification messages promote behavioral changes. These alerts allow the building manager to identify air quality problems and plan interventions to avoid unhealthy air quality scenarios. The proposed architectures incorporate mobile computing technologies such as mobile applications that provide ubiquitous air quality data consulting methods s. Also, the data is stored and can be shared with medical teams to support the diagnosis.

The state-of-the-art analysis has resulted in a review article on technologies, applications, challenges, opportunities, open-source IoT platforms, and operating systems. This review was significant to define the IoT-based Framework for indoor air quality supervision. The research leads to the development and design of cost-effective solutions based on open-source technologies that support Wi-Fi communication and incorporate several advantages such as modularity, scalability, and easy installation. The results obtained are auspicious, representing a significant contribution to enhanced living environments and occupational health.

Particulate matter (PM) is a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air. Moreover, it is considered the pollutant that affects more people. The most damaging particles to health are ≤PM10 (diameter 10 microns or less), which can penetrate and lodge deep within the lungs, contributing to the risk of developing cardiovascular and respiratory diseases as well as lung cancer. Taking into account the adverse health effects of PM exposure, an IoT architecture for automatic PM monitoring was proposed. The proposed architecture is a PM real-time monitoring system and a decision-making tool. The solution consists of a hardware prototype for data acquisition and a Web Framework developed in .NET for data consulting. This system is based on open-source and technologies, with several advantages compared to existing systems, such as modularity, scalability, low-cost and easy installation. The data is stored in a database developed in SQL SERVER using .NET Web services. The results show the ability of the system to analyze the indoor air quality in real-time and the potential of the Web Framework for the planning of interventions to ensure safe, healthy, and comfortable conditions.

Associations of high concentrations of carbon dioxide (CO_2) with low productivity at work and increased health problems are well documented. There is also a clear correlation between high levels of CO_2 and high concentrations of pollutants in indoor air. There are sufficient reasons to monitor CO_2 and provide real-time notifications to improve occupational health and provide a safe and healthy indoor living environment. Taking into account the significant influence of CO_2 for enhanced living environments, a real-time IoT architecture for CO_2 monitoring was proposed. CO_2 was selected because it is easy to measure and is produced in quantity (by people and combustion equipment). It can be used as an indicator of other pollutants and, therefore, of air quality in general. The solution consists of a hardware prototype for data acquisition environment, a Web software, and a smartphone application for data consulting. The proposed architecture is based on open-source technologies, and the data is stored in a SQL SERVER database. The mobile Framework allows the user not only to consult the latest data collected but also to receive real-time notifications in poor indoor air quality scenarios, and to configure the alerts threshold levels. The results show that the mobile application not only provides easy access to real-time air quality data, but also allows the user to maintain parameter history and provide a history of changes. Consequently, this system allows the user to analyze in a precise and detailed manner the behavior of air quality.

Finally, an air quality monitoring solution was implemented, consisting of a hardware prototype that incorporates only the MICS-6814 sensor as the detection unit. This system monitors various air quality parameters such as NH_3 (ammonia), CO (carbon monoxide), NO_2 (nitrogen dioxide), C_3H_8 (propane), C_4H_{10} (butane), CH_4 (methane), H_2 (hydrogen) and C_2H_5OH (ethanol). The monitoring of the concentrations of these pollutants is essential to provide enhanced living environments. This solution is based on Cloud, and the collected data is sent to the ThingSpeak platform. The proposed Framework combines sensitivity, flexibility, and measurement accuracy in real-time, allowing a significant evolution of current air quality controls. The results show that this system provides easy, intuitive, and fast access to air quality data as well as relevant notifications in poor air quality situations to provide real-time intervention and improve occupational health. These data can be accessed by physicians to support diagnoses and correlate the symptoms and health problems of patients with the environment in which they live.

As future work, the results reported in this thesis can be considered as a starting point for the development of a secure system sharing data with health professionals in order to serve as decision support in diagnosis.

Keywords

Air Quality, Ambient Assisted Living, Enhanced Living Environments, Internet of Things, Mobile Applications, Mobile Computing, Monitoring, Open Source Software, Pervasive Systems, Remote Notifications, Ubiquitous Computing

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Acronyms

AAL	Ambient Assisted Living
BLE	Bluetooth Low Energy
C_2H_5OH	Ethanol
C_3H_8	Propane
C_4H_{10}	Butane
CH_4	Methane
CO	Carbon Monoxide
DSL	Digital Subscriber Line
EPC	Electronic Product Codes
EXI	Efficient XML Interchange
GPRS	General Packet Radio Service
H_2	Hydrogen
ICT	Information and communications technology
IoT	Internet of Things
IP	Internet Protocol
LTE	Long-Term Evolution
M2M	Machine to machine
NFC	Near Field Communication
NH_3	Ammonia
NO_2	Nitrogen Dioxide
OWL	Ontology Web Language
PM	Particulate Matter
QoS	Quality of Service
RDF	Resource Description Framework
RFID	Radio-Frequency Identification
uCode	Ubiquitous Code
UMTS	Universal Mobile Telecommunications System
W3C	World Wide Web consortium
WiMax	Worldwide Interoperability for Microwave Access

Chapter 1

Introduction

This thesis addresses the problem of indoor air quality since several sources of pollutants characterize these environments, and typically most people spend more than 90% of their time inside buildings. Therefore, this thesis presents the design and IoT architectures using modular and scalable structures for air quality monitoring based on data from low-cost sensors for enhanced living environments. The proposed architectures incorporate notification management Frameworks that notify the user ubiquitously in real-time in unhealthy indoor quality scenarios. The focus, scope, and research objectives of the thesis are described in this chapter, followed by the thesis statement, the main contributions, and the thesis organization.

1. Thesis Focus and Scope

The basic idea of IoT is the pervasive presence of a variety of objects with interaction and cooperation capabilities among them to reach a common objective [1]. IoT will have a significant impact on several aspects of everyday life and will be used in several applications such as domotics, assisted living, e-health and is also an ideal emerging technology to provide new evolving data and computational resources for creating revolutionary software applications (also known as “apps”) [2]. Systems based on the IoT interact via wireless technologies such as RFID (Radio-Frequency Identification), NFC (Near Field Communication), ZigBee, WSN (Wireless sensor network), DSL (Digital Subscriber Line), WLAN (wireless local area network), WiMax (Worldwide Interoperability for Microwave Access), UMTS (Universal Mobile Telecommunications System), GPRS (General Packet Radio Service), or LTE (Long-Term Evolution). Moreover, IoT presents several challenges to be solved, such as security and privacy, participatory sensing, Big Data, and architecture challenges apart of the known WSN challenges, including energy efficiency, protocols, and Quality of Service (QoS) [2].

Industry applications, monitoring and water control, smart homes’ architecture, estimation of natural disasters, medical systems, agriculture applications, intelligent transport system design, design of smart cities, smart metering and monitoring, smart security are examples of relevant IoT applications [3].

The identification is essential for the development of the IoT systems since it is essential to ensure the correct identification of objects in order to match services with their demand. Several identification methods are available such as electronic product codes (EPC) and ubiquitous code (uCode). Object identification refers to its name or designation and addressing refers to its IP address for communication on the network. Addressing methods include today's IPv4, IPv6, and 6LoWPAN that provides compression on IPv6 headers [4]. With the large address space provided by IPv6, all the addressing needs of the IoT are satisfied.

In IoT, sensing refers to collect data from the environment and to send it to a database, remote, local, or in Cloud. Smart sensors, actuators, or wearable sensors are examples of IoT sensors.

Moreover, communication is an integral part of all IoT devices. The communication is limited by the nature of the "things" themselves, for example, battery life or limited range of data transmission, protocols such as Wi-Fi, ZigBee, GSM, GPRS, UMTS, 3G, LTE and 5G [5]. The IEEE 802.15.4e standard was released by IEEE in 2012 to enhance and add functionality to the previous 802.15.4 standard to address the emerging needs of embedded industrial applications [6]. There are also other communications technologies used for proximity communications, such as RFID [7], NFC [8], and Beacons (Bluetooth Low Energy) [9]. A memoryless-based collision window tree plus (CwT+) protocol for simplified computation in anti-collision radio frequency identification (RFID) is proposed by [10], the authors concluded the outperformance of the CwT+ compared with earlier protocols. Low-cost flexible NFC tags have been proposed to allow everyday objects to communicate with smartphones and computers on IoT scenarios [11]. Bluetooth 4.2 incorporates enhanced features that make Bluetooth Low Energy an appropriate protocol for low-power communication technologies in the IoT and are applied in 6LoWPAN networks [12].

Besides, IoT is deployed using several hardware platforms applications such as Arduino [13], Intel Galileo [14], Raspberry Pi [15], or ESP8266 [16]. Cloud computing platforms are also an essential computational part of the IoT paradigm because they provide facilities for data storing and processing in real-time.

The different IoT services can be categorized as identity-related services, information aggregation services, collaborative-aware services, and ubiquitous services [17]. Identity-related services are focused on the identification of objects, whereas aggregation services collet and summarize sensor data and send them to the backend application. Furthermore, collaborative-aware services are used to transform the obtained data into a decision to respond accordingly, while ubiquitous services aim to provide collaborative-aware services anytime to anyone and anywhere.

Semantic in the IoT is considered as the ability to extract knowledge from machines to provide the required services by discovering and using resources and modelling information. Therefore, Semantic Web technologies examples are the Resource Description Framework (RDF) [18] and the Web Ontology Language (OWL) [19]. In 2011, the World Wide Web Consortium (W3C) adopted the Efficient XML Interchange (EXI) [20] format as a recommendation. EXI converts XML messages to binary in order to reduce the bandwidth and minimize the required storage size.

AAL is an emerging multi-disciplinary field aiming at providing an ecosystem of different types of sensors, computers, mobile devices, wireless networks, and software applications for personal healthcare monitoring and telehealth systems [21]. Currently, different AAL solutions are having as basis several sensors for measuring weight, blood pressure, glucose, oxygen, temperature, location, and position, and they generally use wireless technologies such as ZigBee, Bluetooth, Ethernet, and Wi-Fi.

There are multiple challenges in designing and implementing effective AAL systems such as information architecture, interaction design, human-computer interaction, ergonomics, usability, and accessibility [22]. There are also social and ethical problems such as acceptance by older adults, privacy and security challenges that should be a requirement of all AAL devices. It is also essential to ensure that technology does not replace human care and should be used as an essential complement.

The concept of the “smart city” has recently been introduced as a strategy to encompass modern urban production factors in a common Framework and, in particular, to highlight the importance of Information and Communication Technologies (ICTs) in the last 20 years for enhancing the competitive profile of a city [23]. Nowadays, cities face interesting challenges and problems to meet socio-economic development and life quality objectives and the concept of “smart cities” correspond to answer to these challenges [24]. The smart city is directly related to an emerging strategy to mitigate the problems generated by urban population growth and rapid urbanization [25]. The most relevant issue in smart cities is the non-interoperability of heterogeneous technologies. IoT can provide interoperability to build a unified urban-scale ICT platform for smart cities [26]. The smart city implementation will cause impacts at distinct levels on science, technology, competitiveness, and society, but also will cause ethical issues. The smart city needs to provide access to accurate information, as it becomes crucial when such information is available at a fine spatial scale where individuals can be identified [27]. IoT has a relevant potential for creating new real-life applications and services for the smart city context [28].

Environmental conditions have a significant impact on occupational health. In particular, indoor environments play a significant role in occupational health since individuals typically spent about 90% of their time inside buildings.

In the USA, air quality is regulated by the Environmental Protection Agency. This organization considers that indoor levels of pollutants may be up to 100 times higher than outdoor pollutant levels and ranked poor air quality as one of the top 5 environmental risks to public health [29]. The problem of poor indoor air quality is of utmost importance affecting, in an especially severe form, the poorest people in the world who are most vulnerable, presenting itself as a critical problem for world health such as tobacco use or the challenge of sexually transmitted diseases [30].

High-quality research should continue to focus on indoor air quality to adopt legislation, inspection, and to design mechanisms that act in real-time to improve public health. Theses methods should be incorporated not only in public places such as schools and hospitals but also in private residences and further increase the rigorousness of the building's construction rules. In most scenarios, simple interventions provided by home-owners and building operators can produce significant positive impacts on indoor air. These interventions include the avoidance of smoking indoors, and the use of natural ventilation are essential behaviors that should be taught to children through educational programs that address indoor air quality [31].

Environmental monitoring in general and air quality, in particular, allows the creation of a time-referenced database that can be used to analyze occupant health behaviors. An automated real-time monitoring and reporting system offer several advantages when the purpose is effective changes for enhanced living environments. On the one hand, notification messages promote behavioral changes. These messages warn the occupant to act in real-time, providing measures to improve indoor air quality. On the other hand, this real-time feature allows the building manager to recognize patterns when recurring unhealthy events are detected and implement changes to prevent them from occurring. Also, this data can be shared with medical teams to support diagnostics. Since individuals spend most of their time indoors, therefore, it is necessary to monitor the quality of the environment and plan interventions for enhanced living environments.

The scope of this thesis consists in the development of IoT architectures and methods for the development of automatic monitoring systems for enhanced living environments and occupational health. These systems incorporate pervasive techniques for data access through mobile computing technologies. The proposed architectures are low-cost construction support easy installation and configuration, are modular, scalable, and integrate real-time monitoring data access through mobile Frameworks. These systems aim to create enhanced living environments but are also essential elements for the effective implementation of the smart cities concept.

2. Problem Definition and Research Objectives

The problem studied in this thesis has resulted in the definition and development of low-cost architectures using modular and scalable structures for air quality monitoring based on IoT. The proposed system incorporates an alert management Framework that notifies the user in real-time in poor indoor air quality. The software framework supports several notification methods, such as remote alerts for smartphones using push notifications, SMS, and e-mail. This real-time notification tool offers several advantages when the goal is to achieve practical changes for enhanced living environments. Several sources of pollutants characterize living environments. Consequently, indoor air quality is recognized as a significant variable to be controlled for enhanced living environments and well-being. It is important to note that typically most people spend more than 90% of their time inside buildings, and unhealthy environmental conditions negatively affect performance and productivity.

The adoption of advanced monitoring systems and techniques that aim to create a database with temporal reference for the correct evaluation of the living environments is an essential tool to support the decision and medical diagnosis. Therefore, it is necessary to provide real-time supervision using Frameworks that allow a correct analysis of the indoor environment for enhanced living environments. In most cases, simple interventions provided by occupants can produce substantial positive impacts on air quality, such as avoiding indoor smoking and the correct use of natural ventilation.

Real-time monitoring in indoor living environments is a matter of significant importance also for the creation of other types of applications that use the data that is collected by these systems. This data can be used to support the correct automation of buildings and improve energy efficiency and, therefore, reduce greenhouse gases. At present, indoor air quality monitoring solutions for residential and commercial buildings are expensive and are based on random sampling. However, these procedures are limiting by providing only information related to a specific sampling and being devoid of spatiotemporal behavior. Some of these solutions offer portability and are compact, offering data logging on the equipment itself, but do not allow real-time data consulting for the building managers to enable rapid and efficient intervention to improve occupational health. These solutions do not support mobile data consulting and real-time notifications.

On the one hand, most of the solutions on the market only allow a history of data limited to the device memory and require data downloading and manipulation procedures with specific software. On the other hand, these solutions are extremely accurate and designed for specific industrial activities. The supervision of indoor environments plays a significant role in promoting health and well-being. Consequently, the development of innovative environmental monitoring systems that provide real-time access, visualization, and analysis of data becomes essential.

The main objective of this thesis is the design of new architectures and methods for enhanced living environments that are low-cost, easy to install, modular, and scalable using wireless communication technologies and mobile computing. The proposed methods incorporate several concepts, including acquisition, processing, storage, analysis, and visualization of data. Moreover, the proposed method includes an alert management Framework that notifies the user in real-time and ubiquitously when the air quality is deficient. The software framework supports various alert methods, such as push notifications for smartphones, SMS, and e-mail. On the one hand, the real-time notification mechanism offers several advantages when the goal is to achieve effective changes for enhanced life environments. On the other hand, notification messages promote behavioral changes. In this thesis, different IoT architectures and methods for ambient quality monitoring were developed, specifically for the assessment and analysis of indoor air quality. Several problems have been studied including the monitoring of particulate matter (PM), carbon dioxide (CO_2) and other specific air quality parameters such as NH_3 (ammonia), CO (carbon monoxide), NO_2 (nitrogen dioxide), C_3H_8 (propane) , C_4H_{10} (butane), CH_4 (methane), H_2 (hydrogen) and C_2H_5OH (ethanol).

In order to organize the research work and achieve the main objective of the thesis a set of important intermediate objectives were established:

1. To properly understand and evaluate the IoT paradigm, in particular, the opportunities for numerous IoT applications for healthcare systems. This thesis began with a review of the state of the art. This review has made an analysis of the current state of the art in IoT architectures for healthcare systems focusing on technologies, applications, challenges, opportunities, open-source IoT platforms, and operating systems;

2. Afterward, as the second intermediate objective, an IoT architecture was developed for PM monitoring which includes a Web Framework for data consulting and notifications;

3. As the third intermediate objective, the development of a Framework for the evaluation of indoor quality with the use of carbon dioxide monitoring was proposed. This Framework consists of a monitoring system, Web software and mobile application for data consulting and includes several types of alerts such as SMS, email and remote notifications through the mobile application;

4. Finally, the fourth intermediate objective is the definition and development of an IoT solution for monitoring various parameters of air quality in which data is stored in the Cloud. This framework combines sensitivity, flexibility and measurement accuracy in real-time, allowing a significant evolution of current air quality controls. The proposed system must provide easy, intuitive and fast access to air quality data as well as essential notifications in poor air quality situations to provide real-time intervention for enhanced living environments based on Cloud.

The proposed architectures and methods assume high importance for the creation of enhanced living environments. The proposed architectures and methods assume high importance for the creation of enhanced living environments. The research work included in this thesis aims to offer remote supervision of debilitated people and data consulting for the caregiver or the medical team to support the diagnosis. The notification system allows real-time identification of environment poor-quality scenarios to act in a useful time for enhanced living environments.

3. Thesis Statement

This thesis proposes modular, scalable, and easy to install IoT architectures for indoor air quality monitoring based on data obtained from low-cost sensors for enhanced living environments. Specifically, the thesis argument is:

> Pervasive and automatic supervision of environmental conditions must be assumed as a complex challenge. The living environment quality has a direct impact on health and well-being. However, there are no structured methods for real-time supervision that incorporate an alert management Framework with real-time and ubiquitous notification capabilities in poor indoor quality scenarios. Defining a new Framework that supports multiple notification methods using smartphone alerts, SMS, e-mail, and remote notifications significantly contribute to the creation of enhanced environments and occupational health. These notifications promote behavior changes and allow the identification of environmental quality patterns to plan interventions to promote health and well-being. This system should incorporate mobile computing technologies, such as mobile applications, that provide ubiquitous access to data, hence, advanced tools for consultation and evaluation of data. The data collected can be shared with medical teams to support the diagnosis.

In order to achieve the objectives of the thesis, a review of IoT architectures, technologies, applications, challenges, and future directions for enhanced living environments and healthcare systems was made. This review was conducted mainly on the different concepts involved in the development of healthcare systems. Several IoT architectures and methods were developed for data acquisition, transmission, and storage. After data acquisition, advanced data analysis and visualization tools are developed. These architectures and Framework were designed using mobile computing to design a ubiquitous system that allows access to data anytime, anywhere.

4. Main Contributions

In this section, a brief description of the main scientific contributions of the thesis is presented.

The first contribution is related to the state-of-the-art review of IoT architectures, technologies, applications, challenges, and future directions for enhanced living environments and healthcare systems. This review performs a comprehensive and comparative study of the available IoT platforms and identifies common threads and gaps that open up new, challenging, interesting, and significant research directions. This contribution has been published in Electronics (MDPI) 2019, 8, 1081 (IF 2017: 2.110, Q1 Computer Networks and Communications).

The second contribution of this thesis is the design and development of an IoT architecture for PM monitoring and incorporate a Web Framework for data consulting, analysis, and notifications. This contribution has been published in Int. J. Environ. Res. Public Health (MDPI) 2018, 13, 1152 (IF 2017: 2.145, Q2 Public, Environmental & Occupational Health).

The third contribution of this thesis is the proposal of an IoT architecture for the evaluation of indoor air quality by monitoring carbon dioxide. This architecture consists of a monitoring system, Web and mobile application for data consulting, and several types of alerts such as SMS, email, and remote notifications through the mobile application. This contribution has been published in the Journal of Medical Systems (Springer) 2019, 43, 67 (IF 2017: 2.089, Q2 Health Informatics).

The fourth contribution of this thesis is the development of an IoT architecture to monitor several air quality parameters using a Cloud service for data storage. This architecture provides easy, intuitive, and fast access to air quality data as well as essential notifications in poor air quality situations to provide real-time intervention and improve occupational health. This contribution has been published in Electronics (MDPI) 2019, 8, 170 (IF 2017: 2.110, Q1 Computer Networks and Communications).

5. Thesis Organization

This thesis is organized as follows:

Chapter 1: Introduction

A brief introduction to the thesis is presented including the focus and scope, thesis objectives, thesis statement, and main contributions of the research work.

Chapter 2: Internet of Things Architectures, Technologies, Applications, Challenges, and Future Directions for Enhanced Living Environments and Healthcare Systems: A Review

This chapter consists of the article titled “Internet of Things Architectures, Technologies, Applications, Challenges, and Future Directions for Enhanced Living Environments and Healthcare Systems: A Review” published in Electronics journal. The main concepts involved in the state-of-the-art of IoT architectures for enhanced living environments and healthcare systems with a focus on the technologies, applications, challenges, opportunities, open-source platforms, and operating systems are presented and discussed. This chapter presents a comprehensive and comparative study of the available IoT platforms and identifies common threads and gaps that open up new, challenging, interesting, and significant research directions.

Chapter 3: A System Based on the Internet of Things for Real-time Particle Monitoring in Buildings

This chapter consists of the article titled “A System Based on the Internet of Things for Real-Time Particle Monitoring in Buildings” published in the International Journal of Environmental Research and Public Health. An IoT architecture for PM real-time supervision is presented in this chapter. The proposed architecture is based on open-source technologies, providing a Wi-Fi system, with several advantages such as its modularity, scalability, low-cost, and easy installation. This architecture incorporates a Web Framework for data visualization and remote notifications.

Chapter 4: Indoor Air Quality Assessment Using a CO_2 Monitoring System Based on Internet of Things

This chapter consists of the article titled "Indoor Air Quality Assessment Using a CO_2 Monitoring System Based on Internet of Things" published in the Journal of Medical Systems. This chapter proposes an IoT architecture for indoor air quality assessment composed of a hardware prototype for ambient data collection and a Web and smartphone software for data consulting. This solution is based on open-source technologies with several advantages such as its modularity, scalability, low-cost, and easy installation. The proposed notification method allows to anticipate technical interventions for enhanced living environments.

Chapter 5: A Cost-Effective Air Quality Supervision Solution for Enhanced Living Environments through the Internet of Things

This chapter consists of the article titled "A Cost-Effective Air Quality Supervision Solution for Enhanced Living Environments through the Internet of Things" published in Electronics MDPI journal. An IoT architecture for real-time air quality monitoring composed of an ESP8266 as the communication and processing unit and a MICS-6814 sensor as the sensing unit is presented in Chapter 5. The proposed method incorporates several gases sensorial capabilities such as carbon monoxide, nitrogen dioxide, ethanol, methane, and propane. This architecture incorporates a mobile Framework for data consulting and real-time notifications and uses a Cloud service for data storage.

Chapter 6: Conclusion and Future Work

The results presented throughout the thesis are discussed, the main achievements are summarized, and the future directions are described.

References

[1] D. Giusto, Ed., The internet of things: 20th Tyrrhenian workshop on digital communications. New York: Springer, 2010.

[2] J. Gubbi, R. Buyya, S. Marusic, and M. Palaniswami, "Internet of Things (IoT): A vision, architectural elements, and future directions," Future Generation Computer Systems, vol. 29, no. 7, pp. 1645–1660, Sep. 2013.

[3] R. Khan, S. U. Khan, R. Zaheer, and S. Khan, "Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges," 2012, pp. 257–260.

[4] A. J. Jara, M. A. Zamora, and A. Skarmeta, "Glowbal IP: An Adaptive and Transparent IPv6 Integration in the Internet of Things," Mobile Information Systems, vol. 8, no. 3, 2012.

[5] J. Jermyn, R. P. Jover, I. Murynets, M. Istomin, and S. Stolfo, "Scalability of Machine to Machine systems and the Internet of Things on LTE mobile networks," in World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2015 IEEE 16th International Symposium on a, 2015, pp. 1–9.

[6] D. De Guglielmo, G. Anastasi, and A. Seghetti, "From IEEE 802.15.4 to IEEE 802.15.4e: A Step Towards the Internet of Things," in Advances onto the Internet of Things, vol. 260, S. Gaglio and G. Lo Re, Eds. Springer International Publishing, 2014, pp. 135–152.

[7] R. Falk, F. Kohlmayer, and A. Köpf, Device and method for providing RFID identification data for an authentication server. Google Patents, 2015.

[8] K. Curran, A. Millar, and C. Mc Garvey, "Near field communication," International Journal of Electrical and Computer Engineering, vol. 2, no. 3, p. 371, 2012.

[9] C. Gomez, J. Oller, and J. Paradells, "Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology," Sensors, vol. 12, no. 12, pp. 11734–11753, Aug. 2012.

[10] I. J. Garcia Zuazola, L. Bengtsson, A. Perallos, and H. Landaluce, "Simplified computation in memoryless anti-collision RFID identification protocols," Electronics Letters, vol. 50, no. 17, pp. 1250–1252, Aug. 2014.

[11] K. Myny et al., "16.3 Flexible thin-film NFC tags powered by commercial USB reader device at 13.56MHz," 2015, pp. 1–3.

[12] S. Raza, P. Misra, Z. He, and T. Voigt, "Bluetooth smart: An enabling technology for the Internet of Things," 2015, pp. 155–162.

[13] C. Doukas, Building internet of things with the Arduino. CreateSpace Independent Publishing Platform, 2012.

[14] M. C. Ramon, Intel Galileo and Intel Galileo Gen 2. Springer, 2014.

[15] E. Upton and G. Halfacree, Raspberry Pi user guide. John Wiley & Sons, 2014.

[16] P. Raspaile and V. Keswani, “Integrating Wireless Sensor Network with Open Source Cloud for application of Smart Home.”

[17] M. Gigli and S. Koo, “Internet of Things: Services and Applications Categorization,” Advances in Internet of Things, vol. 01, no. 02, pp. 27–31, 2011.

[18] C. Vertan and R.-F. Merkmale, “Resource description framework (rdf),” 2004.

[19] D. L. McGuinness and F. Van Harmelen, “OWL web ontology language overview,” W3C recommendation, vol. 10, no. 10, p. 2004, 2004.

[20] D. Peintner, H. Kosch, and J. Heuer, “Efficient XML Interchange for rich internet applications,” in Multimedia and Expo, 2009. ICME 2009. IEEE International Conference on, 2009, pp. 149–152.

[21] I. Ganchev, N. M. Garcia, C. Dobre, C. X. Mavromoustakis, and R. Goleva, Eds., Enhanced Living Environments: Algorithms, Architectures, Platforms, and Systems, vol. 11369. Cham: Springer International Publishing, 2019.

[22] C. X. Mavromoustakis, N. M. Garcia, R. I. Goleva, G. Mastorakis, and C. Dobre, Eds., Ambient assisted living and enhanced living environments: principles, technologies and control. Amsterdam ; Boston: Butterworth-Heinemann, 2017.

[23] A. Caragliu, C. Del Bo, and P. Nijkamp, “Smart Cities in Europe,” Journal of Urban Technology, vol. 18, no. 2, pp. 65–82, Apr. 2011.

[24] H. Schaffers, N. Komninos, M. Pallot, B. Trousse, M. Nilsson, and A. Oliveira, “Smart Cities and the Future Internet: Towards Cooperation Frameworks for Open Innovation,” in The Future Internet, vol. 6656, J. Domingue, A. Galis, A. Gavras, T. Zahariadis, D. Lambert, F. Cleary, P. Daras, S. Krco, H. Müller, M.-S. Li, H. Schaffers, V. Lotz, F. Alvarez, B. Stiller, S. Karnouskos, S. Avessta, and M. Nilsson, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 431–446.

[25] H. Chourabi et al., “Understanding Smart Cities: An Integrative Framework,” 45th Hawaii international conference on system sciences. IEEE, 2012, pp. 2289–2297, 2012, pp. 2289–2297.

[26] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, “Internet of Things for Smart Cities,” IEEE Internet of Things Journal, vol. 1, no. 1, pp. 22–32, Feb. 2014.

[27] M. Batty et al., “Smart cities of the future,” The European Physical Journal Special Topics, vol. 214, no. 1, pp. 481–518, Nov. 2012.

[28] J. M. Hernández-Muñoz et al., “Smart Cities at the Forefront of the Future Internet,” in The Future Internet, vol. 6656, J. Domingue, A. Galis, A. Gavras, T. Zahariadis, D. Lambert, F. Cleary, P. Daras, S. Krco, H. Müller, M.-S. Li, H. Schaffers, V. Lotz, F. Alvarez, B. Stiller, S. Karnouskos, S. Avessta, and M. Nilsson, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 447–462.

[29] J. M. Seguel, R. Merrill, D. Seguel, and A. C. Campagna, “Indoor Air Quality,” American Journal of Lifestyle Medicine, p. 1559827616653343, 2016.

[30] N. Bruce, R. Perez-Padilla, and R. Albalak, “Indoor air pollution in developing countries: a major environmental and public health challenge,” Bulletin of the World Health Organization, vol. 78, no. 9, pp. 1078–1092, 2000.

[31] A. P. Jones, “Indoor air quality and health,” Atmospheric Environment, vol. 33, no. 28, pp. 4535–4564, Dec. 1999.

Chapter 2

Internet of Things Architectures, Technologies, Applications, Challenges, and Future Directions for Enhanced Living Environments and Healthcare Systems: A Review

This chapter presents and discusses the main concepts involved in the state-of-the-art of IoT architectures for enhanced living environments and healthcare systems with a focus on the technologies, applications, challenges, opportunities, open-source platforms, and operating systems.

The following article presents the Chapter 2.

Internet of Things Architectures, Technologies, Applications, Challenges, and Future Directions for Enhanced Living Environments and Healthcare Systems: A Review

Gonçalo Marques, Rui Pitarma, Nuno M. Garcia and Nuno Pombo

Electronics (MDPI), published, 2019.

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Review

Internet of Things Architectures, Technologies, Applications, Challenges and Future Directions for Enhanced Living Environments and Healthcare Systems: A Review

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Abstract: Internet of Things (IoT) is an evolution of the Internet and has been gaining increased attention from researchers in both academic and industrial environments. Successive technological enhancements make the development of intelligent systems with a high capacity for communication and data collection possible, providing several opportunities for numerous IoT applications, particularly healthcare systems. Despite all the advantages, there are still several open issues that represent the main challenges for IoT, e.g., accessibility, portability, interoperability, information security, and privacy. IoT provides important characteristics to healthcare systems, such as availability, mobility, and scalability, that offer an architectural basis for numerous high technological healthcare applications, such as real-time patient monitoring, environmental and indoor quality monitoring, and ubiquitous and pervasive information access that benefits health professionals and patients. The constant scientific innovations make it possible to develop IoT devices through countless services for sensing, data fusing, and logging capabilities that lead to several advancements for enhanced living environments (ELEs). This paper reviews the current state of the art on IoT architectures for ELEs and healthcare systems, with a focus on the technologies, applications, challenges, opportunities, open-source platforms, and operating systems. Furthermore, this document synthesizes the existing body of knowledge and identifies common threads and gaps that open up new significant and challenging future research directions.

Keywords: ambient assisted living, enhanced living environments, healthcare; health monitoring; internet of things; ubiquitous and pervasive computing.

1. Introduction

In order to maintain and improve people's life quality in all periods of life but particularly for older adults, ambient assisted living (AAL) remains a multi-disciplinary field that is strictly related to an ecosystem of different technologies and applications for personal healthcare monitoring and pervasive and ubiquitous computing [1,2]. The concept of enhanced living environments (ELEs) refers to the AAL area that is more associated with information and communications technologies (ICTs). ELEs include all ICT achievements to support AAL. ELEs incorporate several ICT solutions, which require algorithms, platforms, and systems to design and develop innovative applications and services to maintain an independent and autonomous living. Moreover, an ELE includes the latest technological achievements related to Internet of Things (IoT) to create ICT solutions to improve people health and well-being. A healthcare system can be defined as a set of hardware and software tools designed to provide a broad range of healthcare services and applications to individuals, such as medical staff and patients, aiming to promote health and well-being in in an effective and often pervasive manner. Healthcare systems are closely related to ELE and AAL. AAL systems present an efficient potential to address several healthcare challenges through ICT. Moreover, ELEs incorporate an ecosystem of healthcare systems, which include medical sensors, microcontrollers, wireless communication technologies, and open-source software platforms, for data visualization and analytics. AAL systems provide pervasive methods and ambient intelligence to design ELE applications that incorporate healthcare systems able to provide 24/7 continuous monitoring and control of the environment. ELE include healthcare systems that directly or indirectly help to maintain people within their home environments instead of being moved into institutionalized environments. Moreover, these systems provide efficient methods to improve individuals' independence and facilitate medical treatments. Currently, there are different healthcare systems that incorporate several technologies to monitor several human physiological status and environmental parameters using different wireless communications technologies, such as ZigBee, 3G, Bluetooth, Ethernet, and Wi-Fi [3]. On the one hand, human physiological status monitoring provides medical state perception and is particularly important for at-risk individuals, such as older adults and newborns, to detect symptoms in useful time. On the other hand, environmental conditions also play a major role in well-being and can be monitored in real-time to detect and prevent dangerous situations. Both monitored data (physiological and environmental) can be analyzed by doctors in order to support clinical diagnostics. In particular, indoor air quality (IAQ) is a significant factor to be monitored and controlled in real-time for ELEs and occupational health as people typically spend about 90% of their time inside buildings. IAQ assessment supports decision making on possible interventions to improve productivity and a healthy indoor environment by identifying multiple situations or habits that affect well-being.

There are several open issues in both the planning and implementation of healthcare systems, such as usability, user interface, data structure, ubiquitous design, ergonomics, and data access [4]. Although there are a number of social and ethical issues, such as acceptance by the users, the privacy and confidentiality of information are already recognized by most healthcare systems [5]. It is likewise imperative to guarantee that technological innovation does not replace human care, and instead it should be used to support medical decisions and monitoring health/diseases anywhere and anytime [6]. By 2050, 20% of the total population will be 60 years old or more [7], and that will bring an increase of healthcare systems' costs and lead to a high dependency on healthcare systems [8]. Likewise, 87% of the general population prefers to stay in their homes instead of moving to a retirement home so they can have better quality of life, and therefore, healthcare systems are also expected to support the high cost of nursing care [9].

IoT architectures refer to the connectivity of physical objects connected to the Internet that support sense capabilities. These objects can be accessed through unique addressing schemes with interaction and cooperation features. IoT architectures incorporate numerous types of devices, such as microcontrollers, sensors, actuators, smartphones, and wearables. Furthermore, open-source platforms, hardware, and enhanced software solutions for data analytics, consulting, management, and storage are required to design and develop IoT architectures. IoT architectures involve people who use these IoT devices and should contribute and cooperate with IoT systems synergistically. Therefore, IoT architectures must be aware of the human context and consider people as an essential part of the system. IoT can support healthcare systems and allow people to stay at home and be supervised in real-time, instead of being sent to nursing homes or clinics [2]. Numerous IoT architectures incorporate personal healthcare devices (PHDs) for remote patient monitoring. These devices are portable systems with relevant features for patient biomedical signal sensing and measurement. The number of PHDs are increasing and must incorporate efficient methods for healthcare servers' connection [10,11]. PHDs are used for activity, blood pressure and pulse oximeters monitoring, medication dispensers, and fall detection [12,13]. These portable devices are used in IoT environments by healthcare staff and allow patient monitoring at home. Moreover, healthcare systems cannot be designed and implemented without the relevant role of PHDs. Moreover, PHDs' integration in healthcare environments is proposed by several studies [14–16]. Several monitoring activities, such as measuring cardiac frequency and blood pressure, that in the past were only available at the hospital, can now be continuously performed by using wearable sensors incorporated in, e.g., smartwatches. However, hospital measurements cannot be completely replaced with wearables, such as smartwatches, for several reasons, such as reliability, accuracy, and the context of the measurement. These wearable sensors should be used as an important complement and will never replace human integration and the relationship between the doctor and the patient.

Healthcare solutions that allow real-time monitoring can avoid unplanned hospitalizations that result in expensive emergency costs. IoT incorporates several advantages for the design and development of healthcare systems. IoT can provide networks of connected devices, Cloud applications, and services to facilitate the patient's monitored data transmission and storage. IoT applications are closely related to healthcare systems through remote monitoring, smart-homes, wearable devices, and smart medical equipment. Numerous academic and industry research studies have been conducted about IoT interoperability and therefore several methods and technologies to address interoperability challenges are available in the literature. These methods focus on the standardization of communication protocols to provide interoperability of heterogeneous devices, networks, and data structures. Therefore, these methods and technologies can also be applied to IoT in order to provide interoperability to the healthcare domain. Furthermore, numerous applications for healthcare have been developed based on IoT, which demonstrates the relevant advantages of this architecture to provide efficient and cost-effective healthcare systems [17]. In order to support high-quality healthcare systems, IoT must adopt standardization, including efficient wireless protocols, improved mobile and wearable sensors, and cost-effective and low-power microprocessors [18]. A study presented by [19] demonstrates that individual approval of IoT advances are broad and growing. The current accessibility of remote wireless medical systems and the emerging diffusion of electronic healthcare database records can make the IoT communication framework the fundamental empowering agent for distributed ubiquitous healthcare applications [20].

This paper aims to provide an introduction to healthcare systems, review the current state of the art, and focus on the technologies, applications, challenges, opportunities, IoT open-source platforms, and operating systems. At this stage, a comprehensive understanding of IoT from a healthcare background is significant in order to support future research. This paper will also present an effective analysis of the key enabling architectures, main applications, challenges, and opportunities for ELEs and healthcare systems. While several survey papers regarding IoT for the healthcare domain are available in the literature and the recent proliferation of IoT platforms is evident, it can also be observed that these surveys do not focus on the examination of existing IoT platforms and operating systems. Therefore, the key novelty of this paper is that it performs a comprehensive and comparative study of the available IoT platforms and operating systems and recommends one of them to specifically address solutions for the healthcare domain. Furthermore, this document synthesizes the existing body of knowledge and identifies common threads and gaps that open up new significant and challenging future research directions for healthcare systems. Taking into account the importance of security, privacy, and quality of service (QoS) open issues in the healthcare field, the paper highlights various insights surrounding healthcare systems. The discussion on numerous key future research topics, with the potential to accelerate the progress and deployment of IoT in healthcare, is expected to provide an important background for future research initiatives. In conclusion, this review article aims to be useful by introducing the topic to not only academics or engineers but also o healthcare professionals, which is essential for the development of future healthcare systems.

The rest of this paper is structured as follows: This paragraph ends Section 1; Section 2 focus on IoT visions, elements, open-source platforms, smartphones, and wearable applications; Section 3 refers to IoT applications in healthcare, and Section 4 focuses on important open issues, such as QoS, security, availability and interoperability; Section 5 discusses several key future research topics with potential to accelerate the progress and deployment of IoT in healthcare systems; and Section 6 concludes the paper.

2. Internet of Things for Healthcare

Healthcare systems are extremely necessary to enhance the global access to healthcare and medical information. Technological innovations facilitate the access to healthcare in an ageing population and also provide new opportunities and methods for processing and knowledge of medical data [21]. Despite all the advantages of healthcare systems, a complex and important open issue associated with the confidentiality and safety of the patients' data still exists [22],[23]. Healthcare systems have several other main challenges e.g. normalization, network setup, business models, QoS and data security as referred by [24]. Several research fields are relevant to the design and implementation of healthcare systems such as mobile and wearable sensors, wireless technologies and open-source platforms (Figure 1). Numerous healthcare systems incorporate mobile and wearable sensors for data collection used for human physiological status monitoring and use wireless communication technologies for data transmission. Moreover, open-source platforms not only support data storage, visualization and analytics but also provide numerous features for device management and security. This section aims to specify a comprehensive summary of the most important areas of research trends in IoT.

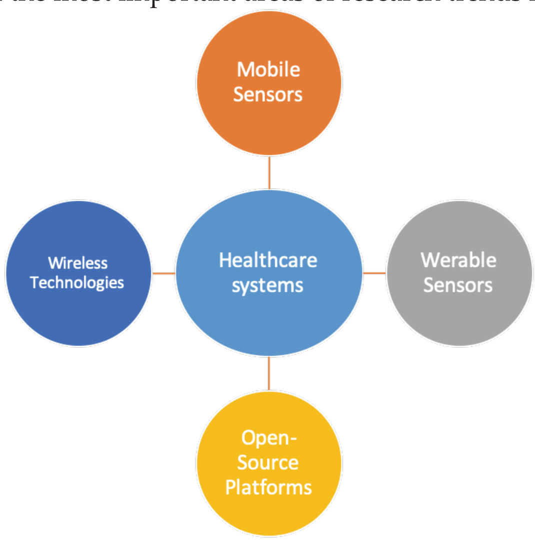

Figure 1 – Important areas of research for healthcare systems.

2.1. Visions

The IoT represents one of the main paradigms in information and communication technologies. IoT has three different points of views: Things-oriented vision, Internet-oriented vision and semantic-oriented vision as referred by [25] (Figure 2). Semantically oriented vision refers to a universal network of unified objects, that supports storage, searches and organizes information. The things-oriented vision refers to intelligent autonomous things applied to our daily lives that are connected to the Internet. The Internet-oriented vision focuses on systems linked to the network with a unique address that supports standard protocols.

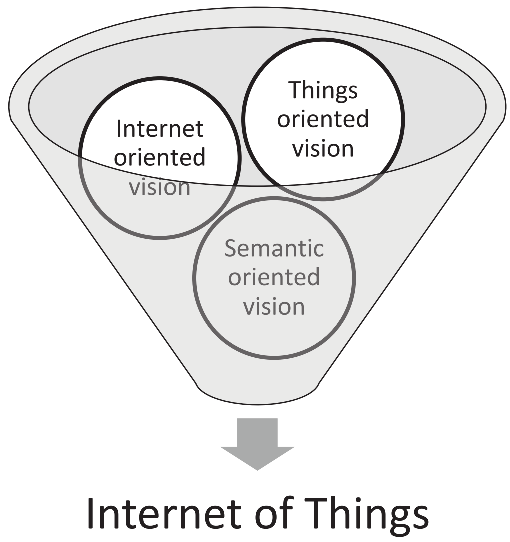

Figure 2 – IoT visions.

Regarding the healthcare systems and applications, things-oriented vision concept is related to the identification of a high diversity of objects, such as sensors and actuators. The Internet-oriented vision is related to methods and procedures to satisfy the data transmission requirements of healthcare systems. Healthcare systems incorporate a high number of sensors, which are responsible for the collection of a massive amount of data. The semantic-oriented vision is related to the methods used to process this vast amount of data in order to extract knowledge to support medical activities.

2.2. Elements

Identification, sensing and communication are the main elements of IoT, elements that will be explained briefly below. Healthcare systems need to be properly identified in order to match services with their demand. Moreover, not only the identification of the physical "things" but also all the interaction entities have to be clearly acknowledged in IoT solutions to ensure the correct composition and operation of the system. Nevertheless, identification has a significant extended scope and is important for all the IoT applications and entities. Identification is a major topic for communication in order to address the items, services, users, data and locations. The "identifiers" are applied to provide identification and can be assumed as a pattern to uniquely identify a single entity in a particular context. Electronic Product Codes (EPC) [26] and ubiquitous code (uCode) [27] are identification methods that currently exist. Object identification refers to hostname and IP address for communication on the network.

Several addressing techniques are present in the literature, such as IPv4, IPv6 and 6LoWPAN that applies compression on IPv6 headers [28]. With the colossal address space offered by IPv6, all the addressing requirements of the IoT are supposed to be met. Sensing is the capture of information from the environment through a collection of data; this data can be saved in a remote, local or cloud database. Communication is a major element of IoT, as for specific applications such as healthcare systems, communication is crucial for patient's data sharing. Currently, there is a vast diversity of communication protocols with different battery dependability and data range transmissions such as Wi-Fi, ZigBee and mobile networks [29]. Most IoT devices adopt the Message Queuing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP). These two open standards are designed to provide mechanisms for asynchronous communication. MQTT is a publish/subscribe messaging protocol designed for lightweight M2M communications. CoAP is a web transfer protocol for use with constrained nodes and constrained networks designed for M2M applications [30,31]. The IEEE 802.15.4e standard was announced by

IEEE in 2012 to improve and complement the previous 802.15.4 standard [32], as to address the emergent requirements of manufacturing and industrial requisites [33]. In particular, the IEEE 802.15.6, is a Wireless Body Area Network (WBAN) standard developed for enhanced health monitoring which supports QoS data rates up to 10Mbps, low power and high reliability [34,35]. Furthermore, other communication technologies are used for short-range communications such as Radio Frequency Identifications (RFID) [36], Near Field Communication (NFC) [37] and Bluetooth Low Energy (BLE) [38]. A memoryless-based collision window tree plus protocol for simplified computation on anti-collision RFID is proposed by [39]. Other technologic enhancements are provided to NFC such as a flexible and cost-effective NFC tag to allow smart devices and daily object communication in IoT environments is referred by [40]. Currently, Bluetooth 4.2 provides a suitable power efficient protocol for IoT and are applied in 6LoWPAN networks [41]. The 6LoWPAN has been projected to support WPAN devices with reduced battery specifications to the Internet and can be used in IoT healthcare systems to facilitate and improve energy efficiency.

The referred IoT elements play an even more important role when applied to the healthcare domain. In fact, healthcare applications based on IoT can significantly enhance patient care, optimize resource consumption, and therefore lead to a decrease in healthcare cost. Regarding the healthcare field, privacy is of principal importance as patient's data must remain confidential. Therefore, identification, sensing and communication elements must incorporate enhanced methods to offer high-quality medical services, while at the same time ensure privacy.

2.3. IoT Open-Source Platforms and Operating Systems

Currently, there are numerous open-source platforms and operating systems that aim to provide support for different systems, data confidentially, safety, fusion and dissemination. This section presents the most relevant IoT platforms and operating systems (Figure 3) which are recognized by their significance for the improvement of state of the art and creative highlights which can likewise be utilized to create secure and scalable healthcare systems.

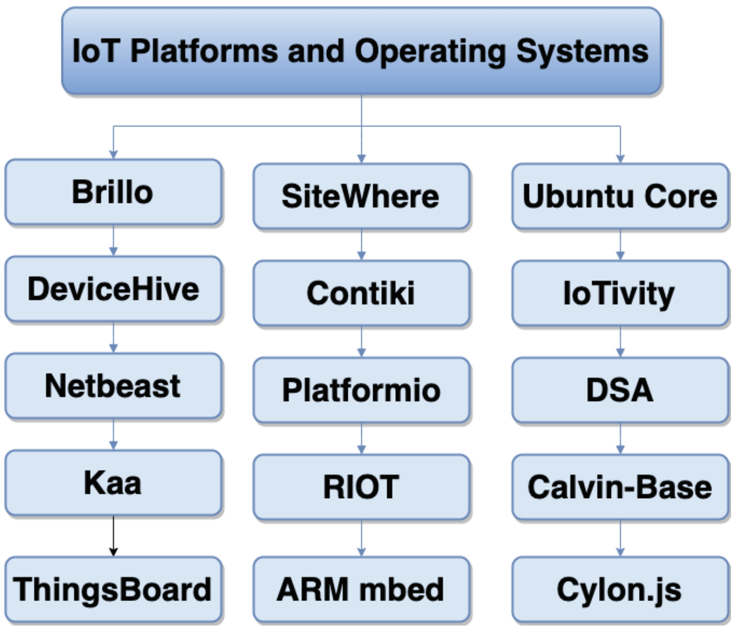

Figure 3 - IoT platforms and operating systems.

1) **SiteWhere:** An open-source IoT platform. It offers a system that accelerates the storage, handling, and incorporation of device data. SiteWhere provides IoT server platform, device management and third-party integration frameworks. This IoT platform aims to provide IoT functionalities for monitoring, automation, and analytics for healthcare systems [42].
2) **DeviceHive:** An open-source IoT data platform that aims to connect devices to the cloud and device data stream. It also provides creation and customization of IoT/M2M (Machine-to-Machine) applications with a secure, scalable and cloud-ready functionalities [43].
3) **Platformio**: An integrated development environment for IoT, supports cross-platform build functionality without external dependencies to the operating system software having compatibility with 200+ embedded boards, 15+ development platforms and 10+ frameworks. It also provides built-in serial port monitor and configurable build flags/options and automatic firmware uploading for IoT systems development [44].
4) **RIOT**: A free, open-source operating system for the majority of the relevant open standards supporting the IoT. It provides code compatibility for 8,16,32-bit platforms, energy-efficiency, real-time capability due to ultra-low interrupt latency, multi-threading with ultra-low threading overhead but also 6LoWPAN, IPv6, IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL), UDP, CoAP and Concise Binary Object Representation (CBOR) protocols [45].
5) **ARM mbed**: An IoT platform that delivers the operating system, cloud facilities, tools and designer ecosystem in order to develop scalable systems based on IoT. It implements safety functionalities such as Transport Layer Security (TLS) as well CoAP and RESTful API to design M2M networks [46].
6) **Ubuntu Core** (Snappy): A development version of Ubuntu for IoT systems that offer safety and extensibility of Ubuntu operating system. It also delivers management systems for safe, reliable, transactional updates controlled by Canonical's AppArmor security system [47].
7) **IoTivity**: An open-source software framework that provides device-to-device communications to the IoT systems. The IoTivity project is sponsored by the Open Connectivity Foundation (OCF), a specification and certification program to address IoT open issues [48].
8) **Distributed Services Architecture** (DSA): An open-source IoT platform that aims to join the heterogeneous hardware and software in IoT and provide a scalable, resilient decentralized solution. DSA is composed of DSBroker, DSLink and nodeAPI. DSBroker acts as a router for incoming and outgoing streams. NodeAPI provides node compatibility and bi-directional control and monitoring ability between connected things. DSLink is connected to the DSBroker that act as the source of the data streams [49].
9) **Calvin-Base:** An open-source platform built with a centralized architecture that supports REST API and it is particularly scalable implementing a variety of plugins for interoperability [50].
10) **Cylon.js:** A JavaScript framework for the IoT that use Node.js. This framework provides code compatibility between different hardware for IoT. Supports multiple platforms such as Arduino, Intel Galileo, Intel Edison and Raspberry [51].
11) **Brillo:** An Android-based operating system, with core services that provide a developer kit and developer console to build IoT applications. It aims to provide scalability with OTA updates, metrics and error reporting. It is supported by the ARM, Intel x86, and MIPS-based hardware but also provide secure services [52].

12) **Contiki:** An open-source operating system for the IoT that provide standard IPv6, IPv4, 6lowpan, RPL and CoAP protocols. This OS provides a network simulation environment for agile IoT development [53].
13) **Netbeast:** An open-source IoT platform that aims to connect IoT devices and to provide agile development for IoT solutions. It is supported by 30 different types of smart home devices and 10 brands such as Philips Hue, Belkin Wenmo, Google Chromecast, Parrot etc [54].
14) **Kaa:** A multi-purpose middleware platform that delivers tools for software development for IoT with enhanced features that decrease related cost, risks, and time-to-market. It is an agnostic hardware solution that supports an SDK for a diversity of programming languages such as C, C++ and JAVA [55].
15) **ThingsBoard:** An open-source IoT platform for data collection, processing, visualization, and device management. This platform supports device connectivity using standard IoT protocols such as MQTT, CoAP and HTTP. Moreover, ThingsBoard support data processing rule chains and alarms configuration based on events, attribute updates, device inactivity and user actions [56].

The achievements of platforms and frameworks are related to different requirements such as [57]:

1. Providing security and privacy APIs with easy configuration and management in order to be adopted by 3rd party systems.
2. Providing interoperability and extendable protocols to be adopted by 3rd party systems.
3. Providing efficient size bandwidth, energy consumptions and low processing requirements.
4. Providing easy management and governance of heterogeneous networks of devices and applications.

Comparison of the IoT platform architectures

An IoT platform is a software designed and developed for specific application domains. It can support several domains such as device management support, security, data collection, integration, analytics, visualization and storage. On the one hand, an IoT platform can provide enhanced features to decrease the development time of IoT applications as it can provide scalability and heterogeneous device compatibility. One the other hand, an IoT platform can connect IoT devices to user applications and provide interaction management between the hardware and the application layers. Regarding the extensive number of IoT platform and operating systems available on the literature is not possible to discuss all related IoT platforms and operating systems. The IoT platforms and operating systems researched in this study have been selected according to the criteria used by the authors of [58] and [59]. Therefore, 15 IoT platforms and operating systems were chosen and analyzed in this paper. In this section, the authors compare the presented open-source IoT platforms and operating systems. The Table 1 presents the comparison results referring to device management support, security, data collection, integration, analytics, visualization and storage features.

Table 1. IoT platforms and operating systems comparison (√: apply; ×: not apply).

IoT Platform	Device Management	Security	Open-Source	Data collection	Integration	Analytics	Visualization	Storage
SiteWhere	√	SSL, Spring Security	√	MQTT, JSON, AMQP, WebSockets	REST API	√	×	√
DeviceHive	√	JSON Web Tokens	√	REST API, MQTT	REST API, MQTT	√	√	√
Platformio	√	SSL	√	REST API, MQTT	Continuous Integration Software	×	×	×
RIOT	×	×	√	COAP,MQTT	REST API	×	×	×
ARM mbed	√	SSL/TLS, X.509 Certificate	√	REST API, MQTT	REST API	×	×	×
Ubuntu Core	√	RSA, SSH	√	MQTT, AMQP	REST API	×	×	√
IoTivity	√	DTLS/TLS	√	Message Queue	REST API	√	×	×
DSA	×	Basic Authentication	√	HTTP	REST API	√	×	√
Calvin-Base	√	×	√	REST API, HTTP	Calvin Script	√	×	×
Cylon.js	√	×	√	REST API, MQTT	REST API	×	×	×
Brillo	√	×	√	REST API	REST API	√	√	√
Contiki	√	×	√	REST API	REST API	√	×	×
Netbeast	√	TLS/SSL	√	HTTP, MQTT	REST API	√	√	√
Kaa	√	TLS/DTLS	√	MQTT,CoAP	REST API	√	√	√
ThingsBoard	√	TLS	√	MQTT, CoAP, HTTP	REST API	√	√	√

After the review of the presented platforms the authors conclude that the majority of the IoT platforms support device management. Considering not only the increase of IoT devices number but also the need to store the atomic attributes of each device the device management feature is extremally important for IoT architectures. These attributes could be the serial number, mac address, location and device firmware version. Is important to note that these attributes can include complex, structured objects, such as a list of connected peripherals and their properties. In addiction, is also important to create groups of IoT devices that are in a specific location and communicate with other devices of the same group. Another important feature related to device management is the authorization mechanism to allow or disable the access remotely. With the exception of RIOT and DSA all the presented platforms support device management.

Regarding security protocols RIOT, Calvin-Base, Cylon.js, Brillo and Contiki do not support native security features. Although, there are 3rd party plugins to manage the security issues of these platforms. In general, all the platforms use MQTT and REST API's to provide data collection and integration features support with the exception of Calvin-Base that uses a specific language syntax script for device configuration and Platformio that use CI (Continuous Integration). CI is the practice, in software engineering, of merging all developer working copies with a shared mainline several times a day. The data analysis and visualization are extremely important features as IoT device generate a lot of data. Platformio, RIOT, ARM mbed, Ubuntu Core and Cylon.js platforms do not have analytics support. The raw and unstructured data collected by IoT devices must be processed in order to create structured data for analytics, pattern analysis, visualization and charting. Consequentially, these platforms are not recommended by the authors for healthcare applications as analytics feature is significant for clinical analysis and diagnosis. Platformio, RIOT, ARM mbed, IoTivity, Calvin-Base, Cylon.js and Contiki platforms do not provide storage features.

For healthcare applications the authors recommend the Kaa platform, this platform support open protocols, encryption channels for data security, provides data analytics, visualization and storage. This platform has important 3rd party integrations based in microservice architecture, is scalable, support open IoT protocols such as MQTT, CoAP and JSON encoding, has gateway support, the communication with devices is secured with TLS or Datagram Transport Layer Security (DTLS), features flexible credentials lifecycle management, supports flexible application versioning and incorporate well-tested open-source components. IoT architectures have been extensively applied in the healthcare domain to implement effective and healthcare systems for older adults and patient monitoring. Moreover, these healthcare systems have been incorporated in ELE to improve users' health and well-being. IoT platforms can provide an efficient functional basis to develop enhanced healthcare systems. These platforms have relevant embedded features for device management, security, data collection, visualization and analytics. Furthermore, IoT platforms implement important features that considerably accelerate healthcare systems development and incorporate embedded scalability and interoperability methods. IoT platforms offer standardization methods for data collection from heterogeneous devices through distinct network protocols. Additionally, some of these platforms support not only remote device configuration and control but also over-the-air firmware updates.

2.4. Smartphones

Currently, smartphones provide considerable processing capabilities and a great diversity of sensors that can be used to develop mobile healthcare systems. A survey of healthcare software for smartphones is presented by [60] and concludes that the use of smartphones in healthcare systems is increasing and are useful applications for patient training, sickness self-administration, and remote supervising. Mobile applications support symptom evaluation, psychoeducation, source position, tracking of treatment development and mental tele-health. Consequently, it is necessary to define and delineate the difference between mobile applications that support healthcare decisions and those with the goal of intervening in clinical decisions [61]. Commercial smartphone applications for healthcare allows patient participation in effective disease prevention and management which leads to significant cost savings in personalized healthcare [62]. Smartphones provide activity recognition through detection of physical activities such as walking and running, climbing stairs, travelling and sedentary behavior without the need of extra devices that can be used for patients activity monitoring for personalized healthcare [63],[64]. A Distributed Particle Filter Simultaneous Localization and Mapping (DPSLAM) process that offers restrictions towards a simple recent mounted inertial measurement unit combined into the mobile phone and specifies the core information on the movement of the user is presented by [65], which can be used to monitor a patient's activity at home after medical intervention. An intelligent communication approach for AAL that uses information collected by sensors, data traffic patterns, and the behavior of a person for providing decisions and send notifications via smartphone applications was proposed by [66] and demonstrates the importance of smartphones in personalized healthcare. The accelerometer, gyroscope or light sensor incorporated in a smartphone can be used for activity recognition and monitoring. The camera and microphone can be used as multimedia sensors for personalized healthcare systems [67]. Smartphones are equipped with short-range communication technologies such as Bluetooth and Wi-Fi but also long-range such as GPRS, UMTS, 3G/4G, that can be used for monitoring co-morbid patients remotely using short-range communication inside hospitals and long-range communication inside the patients' home [68]. The NFC and RFID identification technologies can accelerate healthcare and medicine care procedures, develop enhanced identification protocols that can lead to a reduction of errors in medical diagnostics [69], [70]. The preceding paragraphs are intended to provide facts that support the importance of smartphones in healthcare systems. Smartphones incorporate sensors, communication technologies and processing power that can be used as a complement for healthcare systems enabling better data accessibility and notifications to the patient but also to collect data from the environment.

2.5. Wearables

Wearable sensors are used on a large scale for healthcare systems, such as diagnostic procedures and visualization software to measure and define living environments and real-time personal activity [3]. Wearables have a remarkable diversity of applications in healthcare such as real-time monitoring of pediatric patients with cardio-metabolic problems [71], headband for electroencephalogram (EEG) feeling recognition aiming to estimate the life quality of individuals [72], to detect situations of behavioral anomaly in smart AAL through the collection of movement data combined with the local context [73]. Wearable technologies can be used to reduce the costs of personalized healthcare by providing patient monitoring in their own homes [74]. Wearables are also used for blood pressure monitoring, ring-type heart rate monitoring, and Bluetooth-based electrocardiogram (ECG) monitoring. A tele-home medical solution that incorporates wearables, wireless technologies, and sensor data fusion techniques is presented by [75]. Healthcare systems can be very important to provide ubiquitous healthcare services because they allow continuous access to patient information [76]. Healthcare systems for symbiotic and bio-inspired architectures may enhance the health circumstances and living expectation of an enormous amount of individuals [77]. A wearable pervasive medical supervising solution that utilizes unified ECG, accelerometer and oxygen (SpO2) sensors that provide biological records to be communicated in wireless sensor network using IEEE 802.15.4 to a PC where the data can be displayed and stored is presented by [78]. Non-invasive sensors incorporated in wristbands are used to measure and supervising several biological parameters such as ECG, EEG, Electrodermal (EDA), breathing, and biochemical procedures [79]. These wearable sensors can offer cost-effective answers for remote supervision of ageing individuals at domestic or nursing homes but also increase patient monitoring and care [80]. Wearable computing devices with an embedded camera can determine the user position and orientation by using Visual Odometry and SLAM (Simultaneous Localization and Mapping) techniques to design assisted living systems capable to offer such guidance with on-site augmented reality, without introducing changes in the environment and using off-the-shelf equipment [81].

A system that aims to provide an active and healthy routine for individuals and to advise them with recommendations and important life behavior information that incorporate wearable bio-signals sensors and artificial intelligence algorithms is presented by [82]. HealthMon is a mobile healthcare framework towards access that proposes an affordable, retail wristband for clinical monitoring scenarios *e.g.* dementia, Parkinson's or ageing and it is used to provide health monitoring and contextualized alerts in real-time, presented by [83]. Wearable sensors are used to predict and to monitor patients by combining clinical observations, identification of "abnormal" biological information resulting from patient deterioration [84]. Wearable sensors are used for monitoring academic, sleep, and mental behavior using mobile phones with a classification accuracies ranged from 67-92% [85] (Figure 4).

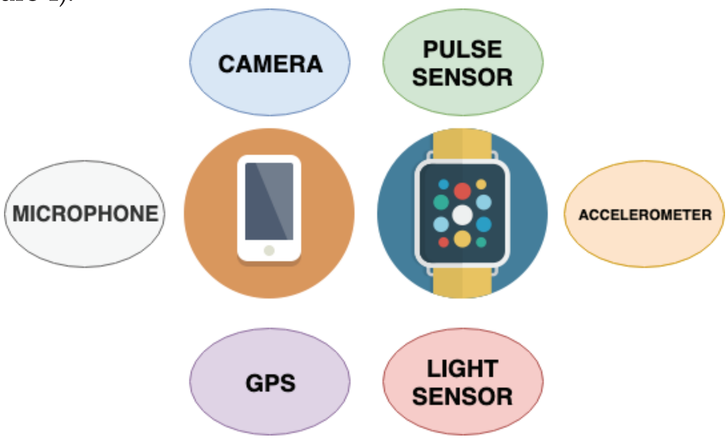

Figure 4 – Mobile sensors.

3. Internet of Things Applications for Healthcare Systems

Smart homes should have cyber-physical content permanent linked to the Internet providing data collection from environment that can be correlated and produce effective knowledge that is used to improve the quality of life of occupants. The MIT Media Lab was responsible for the development of the first smart home project [86]. Smart homes can be classified into different categories depending on their main purpose. On the one hand, several smart homes aim to identify and distinguish the movements of its occupants to improve their health. On the other hand, some smart homes that aims to store and retrieve multi-media captured data in the indoor environment and other activities centered on the surveillance, to be processed in order to obtain information to create real-time notifications and alarms to safeguard family and house. Moreover, another group of smart homes is classified based on energy efficiency concerns by providing energy consumption supervising and gadgets control [87]. A smart home intends to deliver an ELE to its occupants through the incorporation of numerous sensors to monitor the indoor environmental conditions and the inhabitants' activities. Furthermore, smart homes aim to add intelligent functionalities to a home in order to incorporate healthcare systems to assist and improve occupant's health and well-being.

As referred by [88] several visions of smart homes are proposed such as a social view, an instrumental view and a functional view. Smart homes can be seen as an enhanced method to improve the life quality of the occupants, this is referred to as the functional view. Another point of view is the smart home prospective for supervising and decreasing the energy consumption and consequently lower the carbon dioxide emission, this is referred to as the instrumental view. Likewise, smart homes can be seen as a way to improve and enhance the digitalization of our daily routine, this is referred to as the socio-technical view.

An example of a smart house that provides breathing and heart rate supervising is presented by [89], this smart home offers occupants, breathing and heart rate supervision with a typical accuracy of 99%. Several projects based on smart homes are available in Europe such as iDorm [90], Gloucester Smart Home [91], and CareLab [92], which remains notable through its significance for the enhance of state of the art and advanced qualities. An unified architecture for supervision and management of smart houses that recurs to ZigBee is recommended by [93].

The SPHERE Project [94] provides environment, video, and wearable data collection to offer an architecture that uses sensor data fusion to provide identification and administration of several healthcare conditions. An IoT architecture that provides management of the integration and behavior-aware orchestration of devices as services and is cloud based is proposed by [95].

Home Health Hub IoT (H3IoT) provides an architecture for health supervising of ageing home occupants that is cost-effective, easy to use, incorporate simple layered design and is delay tolerant [96]. A healthcare system for diabetes therapy is proposed by [97], this system provide connectivity between the developed patient's device based on 6LoWPAN, the medical team's desktop software to process individual health conditions and a glycemic index information system. Several projects for remote healthcare based on IoT that can improve the process and intelligence of information collection in the medical industry are reported in the literature. One has been proposed by [98]. IoT allows the correct tracking of devices and their identification, patients and clinical team validation, and data collection that produces important information for personalized healthcare [25]. IoT platforms are able to support pervasive healthcare adopting wearable devices for data collection and mobile devices to upload the data to servers, for communication and interfacing with sensors that allow measuring physiological parameters [99]. Healthcare systems based in IoT architectures provide an effective way to monitor, store health and well-being continuously [2] but further offer protocols to be ubiquitous and fully modified for personalized healthcare [100], [101]. UT-GATE offers native capabilities for well-being supervising software such as the local repository, compression, signal processing, data standardization, web services, protocol translation and tunneling, firewall, data mining and notifications, being proposed by [102]. The Health-IoT (in-home healthcare IoT architecture) delivers a business-technology with co-design organization for cross-boundary incorporation for in-home medical systems based in IoT, but have a deficiency of interoperability [103]. The correlation of a diversity of healthcare systems and sensors could provide earlier medical interventions rather than a detection of advanced stage diseases and provide preventive care [100].

Table 2 aims to analyze a number of studies of the current state of the art which will be categorized by application, sensing, configuration setting, connectivity, access to data, results and limitations. Furthermore Table 2 presents a comparison summary which will be analyzed afterwards in order to extract lessons and common threads on the enhanced healthcare systems research.

Table 2. Comparison summary on the presented healthcare systems (×: no support).

Application	Sensing	Configuration setting	Connectivity	Access to data	Results	Limitations	Ref.
Smartphone-centric AAL platform to monitor patients suffering from co-morbidities	Smartphone sensors (accelerometer, GPS, microphone) and external medical devices	Smartphones and others external devices	Wi-Fi, 3G/4G, GPRS and Bluetooth	Mobile application	Smartphone simultaneously used for data collection using built-in sensors and external medical devices but also as processing unit to extract information of interest.	The study does not address the issue related with power consumption and smartphone autonomy.	[68]
Wearable for EEG based detection of emotions	EEG	Head band	ZigBee	×	Wearable headband prototype can harvest sufficient energy to supply power consumption. The proposed study can achieve a classification accuracy of 90%.	Wearable protype size and data accessibility.	[104]
Anomaly detection in human daily activities using wearable sensors	Accelerometer and passive infrared sensors	Mobile robot, fixed sensors and wearable sensors positioned on hand, foot and belt	ZigBee	×	Coherent detection of four different types of daily activity anomalies, such as falling to the ground, not following the normal schedule, working overtime, and sleepwalking.	The study needs further tests on more human subjects and in more realistic environments.	[73]
Wearable ubiquitous healthcare monitoring	ECG, accelerometer and oxygen saturation sensors	Sensor belt and wrist oximeter	ZigBee	Desktop application	The proposed system allows physiological data to be transmitted in wireless and have low power consumption. The collected data can be consulted and stored in real-time.	The study needs further experimental validation. The proposed systems do not have remote data access.	[78]

Application	Sensing	Configuration setting	Connectivity	Access to data	Results	Limitations	Ref.
A system for promoting an active and healthy lifestyle using wearable bio-signals sensors	Blood pressure sensor and accelerometer	Wearable sensors positioned on wrist and smartphone used as a gateway	Wi-Fi, 3G /HSDPA and Bluetooth	Mobile application	This study uses a smartphone to receive data from the wearable sensors but also for data sharing with the backend cloud-based infrastructure for data storage. The proposed system incorporates a website for patient data sharing with both, medical personnel and family caregivers.	No obvious disadvantages	[82]
Mobile health real-time monitoring framework using wearables	Accelerometer, gyroscope, skin temperature, GPS, contact sensor, ultraviolet light and LED-based heart rate sensor	Wearable sensors positioned on wrist and smartphone used as a gateway	Bluetooth, Wi-Fi and 3G	Mobile application	This study proposes a low-cost mobile monitoring wristband for real-time monitoring of physical activity levels, posture detection and heart rate measurements. This solution incorporates instant notification alerts on critical situations and user evaluation tests ensure high acceptability.	Further validation should be done to reliably posture detection for fall detection. The remote notifications should be enhanced in order to provide more intrusive, urgent notifications for family and doctors.	[83]
Personal diabetes management device	Glucometer	Mobile glucometers for data collection and RFID and NFC cards for patient identification	Ethernet, GPRS, Bluetooth, RFID and NFC	Web and Desktop application	This personalized system allows that the measurements and interactions with the patient are done at home. This architecture provides a web portal, and the management desktop application for data consulting.	This study doesn't include a context management framework in order to get additional information about the physical activity, and communication with electronic health record from the hospital information system.	[97]

Application	Sensing	Configuration setting	Connectivity	Access to data	Results	Limitations	Ref.
Intelligent medicine box for in-home healthcare	GPS, compass sensor, accelerometer, video camera, microphone and ECG	Fixed sensors installed in the medicine box and ECG sensor positioned on chest	RFID, NFC, Bluetooth, Wi-Fi and 3G/4G	Web and mobile application	This intelligent medicine box can effectively integrate the in-home health care devices and services. It incorporates a tablet for sensing and connecting.	The proposed methodology needs to be validated in business practices and also to improve the detection speed and accuracy of medication activities.	[105]

Table 3 presents a review summary on the communication technologies used for the design of healthcare systems. The Wi-Fi communication is commonly used to provide Internet connection, however due to energy consumption concerns, it is not used in battery powered systems. The GPRS/3G/HSDPA and 4G are incorporated in the majority of smartphones and are significant to provide Internet connection when Wi-Fi networks are not available. Several healthcare systems are designed to use the smartphone as a gateway, where the data is collected using wearable sensors and is transferred to the smartphone. In these scenarios, the interface commonly used is Bluetooth since this is a low consumption communication technology. Furthermore, RFID and NFC are used to provide identification of the patients or the devices and rarely serve the purpose of transmitting data from one device to the other.

Table 3. Communication technologies used for the design of healthcare systems.

	Wi-Fi	**GPRS/3G/ HDSPA /4G**	**ZigBee**	**Bluetooth**	**RFID**	**NFC**	**Standard Ethernet**
EEG	-	-	[104]	-	-	-	-
ECG	-	-	[78]	-	[105]	[105]	-
Smartphone	[68], [82]	[68], [82]	-	[68], [82]	[105]	[105]	-
Wrist	[82], [83]	[82],[83]	[78], [73]	[82], [83]	-	-	-
Medicine box	[105]	[105]	-	[105]	[105]	[105]	[105]
Glucometer	-	[97]	-	[97]	[97]	[97]	-

From the analysis of Table 3, it is possible to conclude that the least used technology for data communication in these scenarios is cabled Ethernet, followed by ZigBee, this being used in three studies, and the most used technologies, used in six studies are the Bluetooth protocol and the GPRS/ 3G / HDSPA / 4G, being in second place the Wi-Fi. The conclusions are aligned with the requirements for low power consumption, portability and lightweight of the data communication technologies.

4. Internet of Things Challenges and Open Issues for Healthcare systems

Healthcare based applications should incorporate improved mechanisms in order to provide privacy to the patient's information. Several safety weaknesses persist in an M2M communication of IoT architecture because the majority of M2M and IoT systems do not require specifications to perform encryption techniques [106]. There is also a need to ensure correct access to the right individuals at the right time and support safe architectures. Several challenges are related to security, privacy and legal aspects [107,108]. Healthcare systems are normally wireless and presented to people in general, the responsibility of the collected data must be protected and provided only with correct authentication and availability. For that, healthcare systems based in IoT should incorporate hardware and software encryption methods and support privacy policies. The data handled by a PHDs is very sensitive in terms of patient privacy, therefore there is a significant need to provide secure storage methods to prevents its exposure to unauthorized individuals. In this study, two security schemes are proposed. Furthermore, the protocol conversion methods must provide efficient authentication procedures. The protocol conversion proposed by KeeHyun Park et al. [109], implement two security schemes for patient's privacy. The biomedical data obtained are not stored as a single unit but stored in parts in the IoT server. Furthermore, the divided data is saved in the IoT authentication server. Therefore, in order to access the data is necessary to violate both servers. Moreover, the proposed protocol conversion method incorporates an authentication scheme named the Buddy-ACK. This authentication scheme ensures that a specific part of biomedical data can only be accessed if a patient and the medical staff are authorized.

Individuals will remain the essential parts of the IoT architecture and consequently will touch all characteristics of our lives, in specific, medical systems, and due to the enormous scale of devices some safety and privacy challenges will subsist, so therefore the teamwork between the research communities is indispensable [110]. IoT has several QoS challenges such as availability, reliability, mobility, performance, scalability and interoperability, as presented by [25,100,111,112] and are representative challenges for healthcare systems (Figure 5).

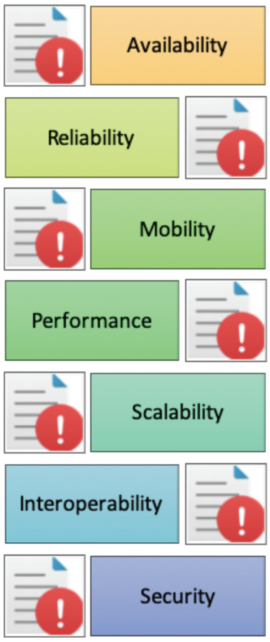

Figure 5 – Healthcare systems open issues.

On the one hand, availability in IoT platforms intends to present everyplace and anytime services to clients. IoT requires interoperability, therefore, must follow the protocols such as IPv6 and 6LoWPA which is preponderant for healthcare systems where availability must be always provided. On the other hand, reliability aims to aggregate the achievement rate of IoT service distribution and is essential to be applied in software and hardware through every part of the IoT layers which are of particular importance for monitoring patients. In addition, mobility intends to relate users with their desired services uninterruptedly, while on the move. Interruption for mobile devices can happen when for example these devices change from one gateway to another. It is essential to develop pervasive and ubiquitous healthcare systems. An IoT-based platform that is compatible with mobility and safety in hospitals is presented by [113]. Performance is a relevant challenge for the implementation of healthcare systems. These systems incorporate a high diversity of heterogeneous devices which collect personal health and medical data. Therefore, healthcare systems must incorporate enhanced methods to provide data security and privacy but in the same must ensure high-performance metrics. Interoperability and scalability play a major role in healthcare systems performance. Furthermore, these systems need to continually improve and increase the performance of healthcare services and meet relevant pervasive and ubiquitous requirements. Scalability signifies the capability to insert new systems and functionality keeping or increasing the QoS as it is extremely important to develop large-scale healthcare systems. In medical environments that assume a huge diversity of hardware platforms and communication protocols, scalability assumes an interesting challenge to develop healthcare systems. Interoperability is a relevant challenge investigated by academia and industry. The industry approach to address interoperability issues has been conducted through standardization [114]. Several methods have been designed to provide interoperability between

IoT devices, services, platforms and data structures. Interoperability plays a major role in IoT development and is particularly relevant in the healthcare domain. Healthcare systems incorporate heterogeneous IoT devices which generate high amounts of data in heterogeneous formats [115]. Therefore, extracting data from different healthcare systems is a complex challenge and interoperability must be ensured to enable heterogeneous systems interaction and is a relevant requirement to solve data heterogeneity issues [116]. Thus, interoperability should be considered by IoT developers and constructors to develop healthcare systems. PHDs and IoT systems use different standard communication protocols for healthcare applications. Several IoT systems use the oneM2M communication protocol as international standard for IoT systems while the PHDs use the ISO/IEEE 11073 protocol. Consequently, communication protocols conversion methods are needed to provide interoperability for healthcare services in ubiquitous environments. Regarding the great number of PHDs used in IoT environments designed using oneM2M protocol, a protocol conversion process between ISO/IEEE 11073 protocol and oneM2M protocol is required. Thus, some protocol conversion studies are presented in the literature. An IoT approach for remote monitoring system for patients at home which incorporates a protocol conversion scheme between ISO/IEEE 11073 protocol and oneM2M protocol and a Multiclass Q-learning scheduling algorithm based on the urgency of biomedical data delivery to medical staff are proposed by [117]. Protocol conversion between ISO/IEEE 11073 protocol messages and oneM2M protocol messages performed in gateways located between PHDs and the healthcare management server is constructed, and evaluated in various experiments by [109].

Healthcare systems are an appropriate method to deal with medical services frameworks, in the light of new research that allows characterizing new propelled strategies for the treatment of numerous sicknesses e.g. by checking of chronic infections to help the medical team to decide the best medications [118]. Regardless of the capability of the IoT view and innovations for medicinal services, there are as yet many difficulties to be settled as showed before, in spite of the fact that, IoT presents an enormous effect on the economy and it is not yet certain if there are limitations to the early and pervasive adoption of IoT frameworks [119].

Security is also an incredible challenge for IoT applications for healthcare environments that are extremely sensible. Healthcare systems based in IoT architecture must be studied on the effect of packet fragmentation and DoS (Denial of Service) attacks [120]. The development of healthcare systems should address technical problems, planning, infrastructure, management and security problems. At the network layer, medical services frameworks should join encryption and avert DoS attacks. IoT has specialized issues as well as arranging, foundation, administration and security issues [121]. At 2008 the ISO/IEC 29192 standards were made so as to contribute light-weight cryptography to devices with reduced specifications, including block and stream cyphers and asymmetric mechanisms. Lightweight cryptography adds to the security of smart devices due to its efficiency and smaller footprint and should be used in healthcare systems that incorporate smart objects with limited processing capabilities [122]. Healthcare systems attacks can be defined as physical, side channel, cryptanalysis, software and network attacks [123] (Figure 6). Physical attacks consist of attacking physical hardware and are the most difficult to achieve. Side channel attacks consist of using data information in order to find the key that the target device is using. Cryptanalysis attacks are based on the ciphertext with the objective of breaking the encryption. Software attacks search for vulnerabilities in system software through its own communication interface. Network communications are exposed against network security attacks because of the broadcast nature of the transmission medium. Most medical IoT-based frameworks combine a few wireless technologies enhancements and are susceptible to numerous security challenges, for example, attacks on secrecy and authentication, silent attacks on service integrity and attacks on network availability. Network availability attacks can be classified as DoS attacks that appear at multiple layers such as physical layer, data-link layer, network layer, transport layer and application layer [124].

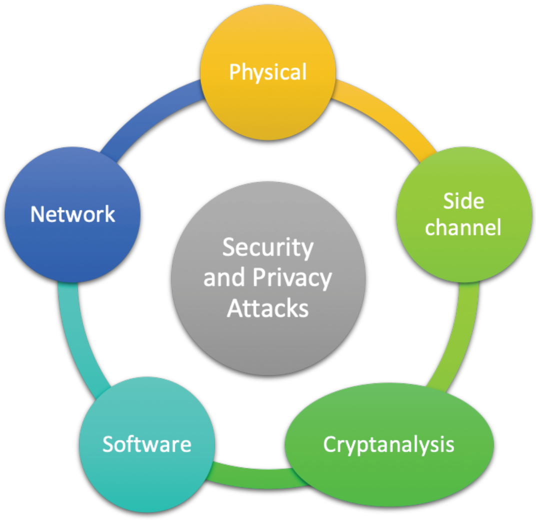

Figure 6 – Security and privacy attacks.

Despite all the concentrated efforts done by numerous researchers on IoT, in particular for healthcare systems, several open issues continue to persist. Cryptographic mechanisms, network protocols, data and identity management, user privacy, self-management, and trusted architectures represent important examples [125]. However, there are also many studies that demonstrate the concern in solving these problems that are presented in the literature [126–132].

5. Discussion and Future Directions

IoT must be assumed as an important and feasible architecture for enhanced healthcare systems. However, several challenges still exist, and research efforts should be made to address usability and user interface; ubiquitous design and ergonomics; data access and data structure; social and ethical issues and security, privacy and QoS for enhanced pervasive and personalized healthcare systems.

Currently, IoT is responsible for an enormous quantity of personal data that is transferred across the Internet without the guarantee of data privacy. Therefore, several ethical and social questions can be raised about transparency at the expense of our privacy. This is an important challenge to be analyzed particularly on healthcare systems in order to provide protection against observation from non-authorized sources [133]. Pervasive monitoring deal with ultra-sensible data about patient well-being and daily routine, therefore the healthcare systems should incorporate strong security methods to guarantee the reliability of the data. Important legislation and regulations should be done in order to guarantee the user's rights, particularly, in the development of healthcare systems. The design of the referred systems should consider ethics as a major factor by adopting policies to ensure that different developers use safe and trustable infrastructures [134]. The healthcare systems data should be protected and implement encryption schemes, key management, appropriate cryptographic and security measures to avoid privacy leakages. Moreover, IoT devices in the healthcare context must be regularly verified to not expose vulnerabilities to security attacks [135].

The proliferation of healthcare services has led to an increase in the amount of data generated which causes design issues on data access and data structure. Therefore, an extra effort must be made to address the complexity and diversity of the data generated by healthcare systems. Furthermore, the diversity of data sources require a uniform standard of heterogeneous data management; the diversity of data content requires a unified programming interface for multiple data analysis modules, and the diversity of service objects require a uniform standard service platform interface as was proposed by [136].

The QoS also play a major role in healthcare systems. Efficient and effective cooperation between the physical and digital domains must be guaranteed in order to provide reliable healthcare systems. The state-of-the art technologies such as 5G offer several opportunities for the IoT, in general, and to healthcare systems, in particular, especially in the real-time applications which involve video on demand [137].

The main application of the enhanced healthcare systems is to develop intelligent and ubiquitous systems for several purposes such as patient's health and well-being monitoring, activity and emotion recognition, anomaly detection in daily routine behavior and specific diseases supervision for ELE and to improve occupational health. Additionally, these systems aim to be used on a large scale which leads to a proliferation of application domains including the development of platforms on healthcare data sharing, visualization and analytics.

The development of enhanced healthcare sensors is closely related to the design and configuration setting of several sensing technologies for efficient and effective data acquisition. Particularly, wearable sensors such EGG, ECG, accelerometers and heart rate sensors are a common trend in the design of enhanced healthcare systems. These sensors are commonly positioned on wrist, belt, hand and/or chest in order to provide ubiquitous sensing. Mobile devices such as smartphones, tablets and smartwatches are simultaneously used for data collection using built-in sensors such as GPS, camera and microphone, but also as a bridge to interface external medical devices. Moreover, the mobile devices have also been used as processing units to transform the collected data into knowledge. Furthermore, assistive robots are also used combined with ambient sensors for activity recognition and monitoring.

The connectivity is extremely relevant as it is responsible to provide data transmission and sharing among the sensing devices and the rest of the equipment in the framework. The majority of healthcare systems are based in wireless communications technologies [138]. The Bluetooth and Zigbee protocols are usually used for device to device communication as well as Wi-Fi and mobile networks technologies such as 3G/4G have been used recurrently to provide Internet access [139].

The access to monitored data is provided using several approaches. On the one hand, the majority of the healthcare systems provides mobile access to the data collected using a web interface. On the other hand, some healthcare systems do not provide remote data access. However, there is a clear tendency to develop systems that can be ubiquitously accessed anywhere, anytime [140,141].

The results of the research on healthcare is promising as it provides real-time patient monitoring solutions as well as it often incorporates off-the-shelf mobile devices as sensing and processing units. It also offers activity and anomaly behavior recognition, real-time notifications and alerts to the medical team and caregivers and a relevant acceptation rate by the users. Particularly, the IAQ monitoring solutions can provide a relevant dataset of the occupant's environmental quality and be correlated with their health status and living environment to support medical diagnostics. Moreover, the real-time monitoring data can be used to generate alerts to advise the occupants to act in a useful time to promote health and well-being. Therefore, there is a relevant need to design and develop cost-effective IAQ solutions based on open-source technologies for ELE and occupational health. However, there are also several limitations such as energy consumption, validation and calibration in real scenarios, modularity and scalability and more effective and ubiquitous notifications to act in useful time for ELE and well-being [142,143].

6. Conclusions

IoT offers new methods, architectures and solutions for enhanced healthcare systems and can be faced with an opportunity to improve medical treatments for personalized healthcare. Open-source platforms and operating systems could improve the quality, security and availability of healthcare systems. Moreover, existing open-source solutions may improve the evolution and efficiency of healthcare systems by also enabling devices, applications and systems to securely expose APIs to external systems. Thus, this will improve interoperability and thus decrease the cost of management and governance of heterogeneous device networks. Currently, there is a large set of very diverse open-source tools that provide secure and cost-effective platforms to develop and prototype new healthcare systems. These can be based in IoT and should provide smartphone and smartwatch compatibility, as these devices are seen today as essential part of daily life and are perceived as extremely important and effective instruments to provide notifications and active coaching in order to improve their users' health and consequently, public health. Mobile devices incorporate today a diversity of sensors that can be used to provide real-time monitoring solutions and data collection to support medical treatments.

Despite all the advantages of healthcare systems, several open issues continue to exist, such as availability, reliability, mobility, performance, scalability and interoperability, among others, and as the evolution of the society will not stop, these will be ongoing open issues because the use case scenarios will not remain static. It is extremely important to refer that this kind of healthcare systems should exist to support medical treatments and as an important complement of medical supervision.

This paper has presented relevant aspects of IoT for healthcare systems such as open-source platforms, operating systems and open issues. It is hoped that a thematic overview has been provided, to introduce not only health and IT professionals but also engineers and students to a paradigm that is essential for the near future in healthcare.

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References

1. Universal Open Platform and Reference Specification for Ambient Assisted Living: http://www.universaal.org/.

2. Dohr, A.; Modre-Opsrian, R.; Drobics, M.; Hayn, D.; Schreier, G. The Internet of Things for Ambient Assisted Living.; IEEE, 2010; pp. 804–809.

3. Al-Janabi, S.; Al-Shourbaji, I.; Shojafar, M.; Shamshirband, S. Survey of main challenges (security and privacy) in wireless body area networks for healthcare applications. Egyptian Informatics Journal 2017, 18, 113–122.

4. Koleva, P.; Tonchev, K.; Balabanov, G.; Manolova, A.; Poulkov, V. Challenges in designing and implementation of an effective Ambient Assisted Living system. In Proceedings of the Telecommunication in Modern Satellite, Cable and Broadcasting Services (TELSIKS), 2015 12th International Conference on; 2015; pp. 305–308.

5. Azimi, I.; Rahmani, A.M.; Liljeberg, P.; Tenhunen, H. Internet of things for remote elderly monitoring: a study from user-centered perspective. Journal of Ambient Intelligence and Humanized Computing 2016.

6. Tenner, E.; Rall, J.E. Why things bite back: Technology and the revenge of unintended

consequences; Vintage Books New York, 1997; ISBN 0-679-74756-7.

7. UN,“Worldpopulationageing:1950–2050,”2001,pp.11–13.

8. Kumar, Rk. Technology and healthcare costs. Annals of Pediatric Cardiology 2011, 4, 84.

9. Centers for Disease Control and Prevention, “The state of aging and health in America 2007,” N. A. on an Aging Society, 2007, Available: https://www.cdc.gov/aging/pdf/saha_2007.pdf.

10. Park, K.; Lim, S. A Multilayer Secure Biomedical Data Management System for Remotely Managing a Very Large Number of Diverse Personal Healthcare Devices. BioMed Research International 2015, 2015, 1–17.

11. Park, K.; Pak, J. An Integrated Gateway for Various PHDs in U-Healthcare Environments. Journal of Biomedicine and Biotechnology 2012, 2012, 1–7.

12. Park, K.; Lim, S. A multipurpose smart activity monitoring system for personalized health services. Information Sciences 2015, 314, 240–254.

13. Pak, J.; Park, K. UbiMMS: An Ubiquitous Medication Monitoring System Based on Remote Device Management Methods. HIM J 2012, 41, 26–30.

14. Arrieta, S.S.; Parra, O.J.S.; Chaves, R.M.P. Design of PHD Solution Based on HL7 and IoT. In Future Data and Security Engineering; Dang, T.K., Küng, J., Wagner, R., Thoai, N., Takizawa, M., Eds.; Springer International Publishing: Cham, 2018; Vol. 11251, pp. 405–409 ISBN 978-3-030-03191-6.

15. Liu, L.; Stroulia, E.; Nikolaidis, I.; Miguel-Cruz, A.; Rios Rincon, A. Smart homes and home health monitoring technologies for older adults: A systematic review. International Journal of Medical Informatics 2016, 91, 44–59.

16. Evans, J.; Papadopoulos, A.; Silvers, C.T.; Charness, N.; Boot, W.R.; Schlachta-Fairchild, L.; Crump, C.; Martinez, M.; Ent, C.B. Remote Health Monitoring for Older Adults and Those with Heart Failure: Adherence and System Usability. Telemedicine and e-Health 2016, 22, 480–488.

17. Ullah, F.; Habib, M.A.; Farhan, M.; Khalid, S.; Durrani, M.Y.; Jabbar, S. Semantic interoperability for big-data in heterogeneous IoT infrastructure for healthcare. Sustainable Cities and Society 2017, 34, 90–96.

18. F. Fernandez; G. C. Pallis Opportunities and challenges of the Internet of Things for healthcare: Systems engineering perspective. In Proceedings of the Wireless Mobile Communication and Healthcare (Mobihealth), 2014 EAI 4th International Conference on; 2014; pp. 263–266.

19. V. Jones; V. Gay; P. Leijdekkers Body Sensor Networks for Mobile Health Monitoring: Experience in Europe and Australia. In Proceedings of the 2010 Fourth International Conference on Digital Society; IEEE: St. Maarten, Netherlands Antilles, 2010; pp. 204–209.

20. Bui, N.; Zorzi, M. Health care applications: a solution based on the internet of things.; ACM Press, 2011; pp. 1–5.

21. Haux, R. Health information systems - past, present, future. Int J Med Inform 2006, 75, 268–281.

22. Chen, D.; Zhao, H. Data Security and Privacy Protection Issues in Cloud Computing.; IEEE, 2012; pp. 647–651.

23. Appari, A.; Johnson, M.E. Information security and privacy in healthcare: current state of research.

International journal of Internet and enterprise management 2010, 6, 279–314.

24. Riazul Islam, S.M.; Daehan Kwak; Humaun Kabir, M.; Hossain, M.; Kyung-Sup Kwak The Internet of Things for Health Care: A Comprehensive Survey. IEEE Access 2015, 3, 678–708.

25. Atzori, L.; Iera, A.; Morabito, G. The Internet of Things: A survey. Computer Networks 2010, 54, 2787–2805.

26. Brock, D.L. The electronic product code (epc). Auto-ID Center White Paper MIT-AUTOID-WH-002 2001.

27. Sakamura, K.; Koshizuka, N. Ubiquitous computing technologies for ubiquitous learning.; IEEE, 2005; pp. 11–20.

28. Jara, A.J.; Zamora, M.A.; Skarmeta, A. Glowbal IP: An Adaptive and Transparent IPv6 Integration in the Internet of Things. Mobile Information Systems 2012, 8.

29. Jermyn, J.; Jover, R.P.; Murynets, I.; Istomin, M.; Stolfo, S. Scalability of Machine to Machine systems and the Internet of Things on LTE mobile networks. In Proceedings of the World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2015 IEEE 16th International Symposium on a; IEEE, 2015; pp. 1–9.

30. Naik, N. Choice of effective messaging protocols for IoT systems: MQTT, CoAP, AMQP and HTTP. In Proceedings of the 2017 IEEE International Systems Engineering Symposium (ISSE); IEEE: Vienna, Austria, 2017; pp. 1–7.

31. van der Westhuizen, H.W.; Hancke, G.P. Practical Comparison between COAP and MQTT - Sensor to Server level. In Proceedings of the 2018 Wireless Advanced (WiAd); IEEE: London, 2018; pp. 1–6.

32. Molisch, A.F.; Balakrishnan, K.; Chong, C.-C.; Emami, S.; Fort, A.; Karedal, J.; Kunisch, J.; Schantz, H.; Schuster, U.; Siwiak, K. IEEE 802.15. 4a channel model-final report. IEEE P802 2004, 15, 0662.

33. De Guglielmo, D.; Anastasi, G.; Seghetti, A. From IEEE 802.15.4 to IEEE 802.15.4e: A Step Towards the Internet of Things. In Advances onto the Internet of Things; Gaglio, S., Lo Re, G., Eds.; Advances in Intelligent Systems and Computing; Springer International Publishing, 2014; Vol. 260, pp. 135–152 ISBN 978-3-319-03991-6.

34. Saboor, A.; Ahmad, R.; Ahmed, W.; Kiani, A.K.; Moullec, Y.L.; Alam, M.M. On Research Challenges in Hybrid Medium Access Control Protocols for IEEE 802.15.6 WBANs. IEEE Sensors Journal 2018, 1–1.

35. Manna, T.; Saha Misra, I. Performance Analysis of Scheduled Access Mode of the IEEE 802.15.6 MAC Protocol under Non-Ideal Channel Conditions. IEEE Transactions on Mobile Computing 2019, 1–1.

36. Falk, R.; Kohlmayer, F.; Köpf, A. Device and method for providing RFID identification data for an authentication server; Google Patents, 2015;

37. Curran, K.; Millar, A.; Mc Garvey, C. Near field communication. International Journal of Electrical and Computer Engineering 2012, 2, 371.

38. Gomez, C.; Oller, J.; Paradells, J. Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology. Sensors 2012, 12, 11734–11753.

39. Garcia Zuazola, I.J.; Bengtsson, L.; Perallos, A.; Landaluce, H. Simplified computation in memoryless anti-collision RFID identification protocols. Electronics Letters 2014, 50, 1250–1252.

40. Myny, K.; Cobb, B.; van der Steen, J.-L.; Tripathi, A.K.; Genoe, J.; Gelinck, G.; Heremans, P. 16.3

Flexible thin-film NFC tags powered by commercial USB reader device at 13.56MHz.; IEEE, 2015; pp. 1–3.

41. Raza, S.; Misra, P.; He, Z.; Voigt, T. Bluetooth smart: An enabling technology for the Internet of Things.; IEEE, 2015; pp. 155–162.

42. SiteWhere The open platform for the Internet of things Available online: https://sitewhere.io/en/ (accessed on Sep 7, 2019).

43. DeviceHive Available online: http://devicehive.com/ (accessed on Sep 7, 2019).

44. Kravets, I. PlatformIO: An open source ecosystem for IoT development Available online: http://platformio.org/ (accessed on Sep 7, 2019).

45. 2016 Riot-OS Available online: https://riot-os.org/ (accessed on Sep 7, 2019).

46. Toulson, R.; Wilmshurst, T. Fast and effective embedded systems design: applying the ARM mbed; Elsevier, 2012; ISBN 0-08-097769-3.

47. Shuttleworth, M.; Ubuntu; Canonical Ubuntu developer portal Available online: https://ubuntu.com/core (accessed on Sep 7, 2019).

48. iotivity Available online: https://www.iotivity.org/ (accessed on Sep 7, 2019).

49. Initiative, D. Distributed Services Architecture (DSA) Available online: http://iot-dsa.org/ (accessed on Sep 7, 2019).

50. Calvin-Base Available online: https://github.com/EricssonResearch/calvin-base (accessed on Sep 7, 2019).

51. Group, T.H. cylonjs Available online: https://cylonjs.com/ (accessed on Sep 7, 2019).

52. Brillo | Google developers Available online: https://developers.google.com/brillo/ (accessed on Sep 7, 2019).

53. Contiki Contiki Available online: https://www.contiki.com/ (accessed on Sep 7, 2019).

54. Netbeast Available online: https://netbeast.co/ (accessed on Sep 7, 2019).

55. Terms, 2016 CyberVision; Conditions Kaa open-source IoT platform — IoT cloud platform the Internet of things solutions and applications that set the standard Available online: http://www.kaaproject.org/ (accessed on Sep 7, 2019).

56. THINGSBOARD - OPEN-SOURCE IOT PLATFORM Available online: https://thingsboard.io (accessed on Sep 7, 2019).

57. Derhamy, H.; Eliasson, J.; Delsing, J.; Priller, P. A survey of commercial frameworks for the Internet of Things.; IEEE, 2015; pp. 1–8.

58. Ray, P.P. A survey of IoT cloud platforms. Future Computing and Informatics Journal 2016, 1, 35–46.

59. Ammar, M.; Russello, G.; Crispo, B. Internet of Things: A survey on the security of IoT frameworks. Journal of Information Security and Applications 2018, 38, 8–27.

60. Luxton, D.D.; McCann, R.A.; Bush, N.E.; Mishkind, M.C.; Reger, G.M. mHealth for mental health: Integrating smartphone technology in behavioral healthcare. Professional Psychology: Research and Practice 2011, 42, 505–512.

61. Charani, E.; Castro-Sánchez, E.; Moore, L.S.; Holmes, A. Do smartphone applications in healthcare

require a governance and legal framework? It depends on the application! BMC Medicine 2014, 12.

62. Vashist, S.; Schneider, E.; Luong, J. Commercial Smartphone-Based Devices and Smart Applications for Personalized Healthcare Monitoring and Management. Diagnostics 2014, 4, 104–128.

63. Anjum, A.; Ilyas, M.U. Activity recognition using smartphone sensors. In Proceedings of the Consumer Communications and Networking Conference (CCNC), 2013 IEEE; 2013; pp. 914–919.

64. Shoaib, M.; Scholten, H.; Havinga, P.J.M. Towards Physical Activity Recognition Using Smartphone Sensors. In Proceedings of the Ubiquitous Intelligence and Computing, 2013 IEEE 10th International Conference on and 10th International Conference on Autonomic and Trusted Computing (UIC/ATC); 2013; pp. 80–87.

65. Faragher, R.M.; Sarno, C.; Newman, M. Opportunistic radio SLAM for indoor navigation using smartphone sensors. In Proceedings of the Position Location and Navigation Symposium (PLANS), 2012 IEEE/ION; 2012; pp. 120–128.

66. Lloret, J.; Canovas, A.; Sendra, S.; Parra, L. A smart communication architecture for ambient assisted living. Communications Magazine, IEEE 2015, 53, 26–33.

67. Parra, L.; Sendra, S.; Jiménez, J.; Lloret, J. Multimedia sensors embedded in smartphones for ambient assisted living and e-health. Multimed Tools Appl 2015, 1–27.

68. Bisio, I.; Lavagetto, F.; Marchese, M.; Sciarrone, A. Smartphone-centric ambient assisted living platform for patients suffering from co-morbidities monitoring. Communications Magazine, IEEE 2015, 53, 34–41.

69. Lahtela, A.; Hassinen, M.; Jylha, V. RFID and NFC in healthcare: Safety of hospitals medication care.; IEEE, 2008; pp. 241–244.

70. Iglesias, R.; Parra, J.; Cruces, C.; de Segura, N.G. Experiencing NFC-based touch for home healthcare.; ACM Press, 2009; pp. 1–4.

71. Yan, K.; Tracie, B.; Marie-Ève, M.; Mélanie, H.; Jean-Luc, B.; Benoit, T.; St-Onge, M.; Marie, L. Innovation through Wearable Sensors to Collect Real-Life Data among Pediatric Patients with Cardiometabolic Risk Factors. International Journal of Pediatrics 2014, 2014, 9.

72. Joseph W Matiko and Yang Wei and Russel Torah and Neil Grabham and Gordon Paul and Stephen Beeby and John Tudor Wearable EEG headband using printed electrodes and powered by energy harvesting for emotion monitoring in ambient assisted living. Smart Materials and Structures 2015, 24, 125028.

73. Chun Zhu; Weihua Sheng; Meiqin Liu Wearable Sensor-Based Behavioral Anomaly Detection in Smart Assisted Living Systems. Automation Science and Engineering, IEEE Transactions on 2015, 12, 1225–1234.

74. Aced López, S.; Corno, F.; De Russis, L. Supporting caregivers in assisted living facilities for persons with disabilities: a user study. Univ Access Inf Soc 2015, 14, 133–144.

75. Hung, K.; Zhang, Y.T.; Tai, B. Wearable medical devices for tele-home healthcare.; IEEE, 2004; Vol. 4, pp. 5384–5387.

76. Kang, D.-O.; Lee, H.-J.; Ko, E.-J.; Kang, K.; Lee, J. A Wearable Context Aware System for Ubiquitous Healthcare.; IEEE, 2006; pp. 5192–5195.

77. Darwish, A.; Hassanien, A.E. Wearable and Implantable Wireless Sensor Network Solutions for Healthcare Monitoring. Sensors 2011, 11, 5561–5595.

78. Wan-Young Chung; Young-Dong Lee; Sang-Joong Jung A wireless sensor network compatible wearable u-healthcare monitoring system using integrated ECG, accelerometer and SpO2.; IEEE, 2008; pp. 1529–1532.

79. Acampora, G.; Cook, D.J.; Rashidi, P.; Vasilakos, A.V. A Survey on Ambient Intelligence in Health Care. Proceedings of the IEEE. Institute of Electrical and Electronics Engineers 2013, 101, 2470–2494.

80. Bandodkar, A.J.; Wang, J. Non-invasive wearable electrochemical sensors: a review. Trends in Biotechnology 2014, 32, 363–371.

81. Saracchini, R.F.V.; Catalina, C.A. An augmented reality platform for wearable assisted living systems. Journal of Theoretical and Applied Computer Science 2015, 9, 56–79.

82. Páez, D.; de Buenaga Rodríguez, M.; Sánz, E.; Villalba, M.; Gil, R. Big Data Processing Using Wearable Devices for Wellbeing and Healthy Activities Promotion. In Ambient Assisted Living. ICT-based Solutions in Real Life Situations; Cleland, I., Guerrero, L., Bravo, J., Eds.; Lecture Notes in Computer Science; Springer International Publishing, 2015; Vol. 9455, pp. 196–205 ISBN 978-3-319-26409-7.

83. Stavropoulos, T.G.; Meditskos, G.; Andreadis, S.; Kompatsiaris, I. Real-time health monitoring and contextualised alerts using wearables. In Proceedings of the Interactive Mobile Communication Technologies and Learning (IMCL), 2015 International Conference on; 2015; pp. 358–363.

84. Clifton, L.; Clifton, D.A.; Pimentel, M.A.F.; Watkinson, P.J.; Tarassenko, L. Predictive Monitoring of Mobile Patients by Combining Clinical Observations With Data From Wearable Sensors. Biomedical and Health Informatics, IEEE Journal of 2014, 18, 722–730.

85. Sano, A.; Phillips, A.J.; Yu, A.Z.; McHill, A.W.; Taylor, S.; Jaques, N.; Czeisler, C.A.; Klerman, E.B.; Picard, R.W. Recognizing academic performance, sleep quality, stress level, and mental health using personality traits, wearable sensors and mobile phones. In Proceedings of the Wearable and Implantable Body Sensor Networks (BSN), 2015 IEEE 12th International Conference on; 2015; pp. 1–6.

86. Moukas, A.; Zacharia, G.; Guttman, R.; Maes, P. Agent-Mediated Electronic Commerce: An MIT Media Laboratory Perspective. International Journal of Electronic Commerce 2000, 4, 5–21.

87. De Silva, L.C.; Morikawa, C.; Petra, I.M. State of the art of smart homes. Engineering Applications of Artificial Intelligence 2012, 25, 1313–1321.

88. Wilson, C.; Hargreaves, T.; Hauxwell-Baldwin, R. Smart homes and their users: a systematic analysis and key challenges. Personal Ubiquitous Comput. 2015, 19, 463–476.

89. Adib, F.; Mao, H.; Kabelac, Z.; Katabi, D.; Miller, R.C. Smart Homes that Monitor Breathing and Heart Rate. In Proceedings of the Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems; ACM: Seoul, Republic of Korea, 2015; pp. 837–846.

90. Pounds-Cornish, A.; Holmes, A. The iDorm - A Practical Deployment of Grid Technology. In Proceedings of the Cluster Computing and the Grid, 2002. 2nd IEEE/ACM International Symposium on; 2002; pp. 470–470.

91. Orpwood, R.; Gibbs, C.; Adlam, T.; Faulkner, R.; Meegahawatte, D. The Gloucester Smart House

for People with Dementia — User-Interface Aspects. In Designing a More Inclusive World; Keates, S., Clarkson, J., Langdon, P., Robinson, P., Eds.; Springer London, 2004; pp. 237–245 ISBN 978-1-4471-1046-0.

92. Henkemans, O.B.; Caine, K.E.; Rogers, W.A.; Fisk, A.D. Medical monitoring for independent living: user-centered design of smart home technologies for older adults. In Proceedings of the Proc. Med-e-Tel Conf. eHealth, Telemedicine and Health Information and Communication Technologies; 2007; pp. 18–20.

93. Suryadevara, N.K.; Kelly, S.; Mukhopadhyay, S.C. Ambient Assisted Living Environment Towards Internet of Things Using Multifarious Sensors Integrated with XBee Platform. In Internet of Things; Mukhopadhyay, S.C., Ed.; Smart Sensors, Measurement and Instrumentation; Springer International Publishing, 2014; Vol. 9, pp. 217–231 ISBN 978-3-319-04222-0.

94. Ni Zhu; Diethe, T.; Camplani, M.; Lili Tao; Burrows, A.; Twomey, N.; Kaleshi, D.; Mirmehdi, M.; Flach, P.; Craddock, I. Bridging e-Health and the Internet of Things: The SPHERE Project. Intelligent Systems, IEEE 2015, 30, 39–46.

95. Cubo, J.; Nieto, A.; Pimentel, E. A Cloud-Based Internet of Things Platform for Ambient Assisted Living. Sensors 2014, 14, 14070–14105.

96. Ray, P.P. Home Health Hub Internet of Things (H3IoT): An architectural framework for monitoring health of elderly people. In Proceedings of the Science Engineering and Management Research (ICSEMR), 2014 International Conference on; 2014; pp. 1–3.

97. Jara, A.J.; Zamora, M.A.; Skarmeta, A.F. An internet of things---based personal device for diabetes therapy management in ambient assisted living (AAL). Personal Ubiquitous Comput. 2011, 15, 431–440.

98. Jingran Luo; Yulu Chen; Kai Tang; Junwen Luo Remote monitoring information system and its applications based on the Internet of Things. In Proceedings of the BioMedical Information Engineering, 2009. FBIE 2009. International Conference on Future; 2009; pp. 482–485.

99. Gubbi, J.; Buyya, R.; Marusic, S.; Palaniswami, M. Internet of Things (IoT): A vision, architectural elements, and future directions. Future Generation Computer Systems 2013, 29, 1645–1660.

100. Miorandi, D.; Sicari, S.; De Pellegrini, F.; Chlamtac, I. Internet of things: Vision, applications and research challenges. Ad Hoc Networks 2012, 10, 1497–1516.

101. Domingo, M.C. Review: An overview of the Internet of Things for people with disabilities. J. Netw. Comput. Appl. 2012, 35, 584–596.

102. Rahmani, A.-M.; Thanigaivelan, N.K.; Tuan Nguyen Gia; Granados, J.; Negash, B.; Liljeberg, P.; Tenhunen, H. Smart e-Health Gateway: Bringing intelligence to Internet-of-Things based ubiquitous healthcare systems.; IEEE, 2015; pp. 826–834.

103. Pang, Z.; Zheng, L.; Tian, J.; Kao-Walter, S.; Dubrova, E.; Chen, Q. Design of a terminal solution for integration of in-home health care devices and services towards the Internet-of-Things. Enterprise Information Systems 2015, 9, 86–116.

104. Matiko, J.W.; Wei, Y.; Torah, R.; Grabham, N.; Paul, G.; Beeby, S.; Tudor, J. Wearable EEG headband using printed electrodes and powered by energy harvesting for emotion monitoring in ambient assisted living. Smart Materials and Structures 2015, 24, 125028.

105. Domingo, M.C. An overview of the Internet of Things for people with disabilities. Journal of

Network and Computer Applications 2012, 35, 584–596.

106. Lake, D.; Milito, R.; Morrow, M.; Vangheese, R. Internet of Things: Architectural framework for eHealth security. Journal of ICT 2014, 3, 301–330.

107. Roy, A.; Roy, C.; Misra, S.; Rahulamathavan, Y.; Rajarajan, M. CARE: Criticality-Aware Data Transmission in CPS-Based Healthcare Systems. In Proceedings of the 2018 IEEE International Conference on Communications Workshops (ICC Workshops); IEEE: Kansas City, MO, USA, 2018; pp. 1–6.

108. Rahulamathavan, Y.; Phan, R.C.-W.; Rajarajan, M.; Misra, S.; Kondoz, A. Privacy-preserving blockchain based IoT ecosystem using attribute-based encryption. In Proceedings of the 2017 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS); IEEE: Bhubaneswar, 2017; pp. 1–6.

109. Woo, M.W.; Lee, J.; Park, K. A reliable IoT system for Personal Healthcare Devices. Future Generation Computer Systems 2018, 78, 626–640.

110. Stankovic, J.A. Research Directions for the Internet of Things. Internet of Things Journal, IEEE 2014, 1, 3–9.

111. Al-Fuqaha, A.; Guizani, M.; Mohammadi, M.; Aledhari, M.; Ayyash, M. Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications. IEEE Communications Surveys & Tutorials 2015, 17, 2347–2376.

112. Khan, R.; Khan, S.U.; Zaheer, R.; Khan, S. Future Internet: The Internet of Things Architecture, Possible Applications and Key Challenges.; IEEE, 2012; pp. 257–260.

113. Valera, A.J.J.; Zamora, M.A.; Skarmeta, A.F.G. An Architecture Based on Internet of Things to Support Mobility and Security in Medical Environments.; IEEE, 2010; pp. 1–5.

114. Noura, M.; Atiquzzaman, M.; Gaedke, M. Interoperability in Internet of Things: Taxonomies and Open Challenges. Mobile Netw Appl 2019, 24, 796–809.

115. Mavrogiorgou, A.; Kiourtis, A.; Perakis, K.; Pitsios, S.; Kyriazis, D. IoT in Healthcare: Achieving Interoperability of High-Quality Data Acquired by IoT Medical Devices. Sensors 2019, 19, 1978.

116. Liu, Y.; Zhou, G. Key Technologies and Applications of Internet of Things.; IEEE, 2012; pp. 197–200.

117. Park, K.; Park, J.; Lee, J. An IoT System for Remote Monitoring of Patients at Home. Applied Sciences 2017, 7, 260.

118. Chui, M.; Löffler, M.; Roberts, R. The internet of things. McKinsey Quarterly 2010, 2, 1–9.

119. Swan, M. Sensor Mania! The Internet of Things, Wearable Computing, Objective Metrics, and the Quantified Self 2.0. Journal of Sensor and Actuator Networks 2012, 1, 217–253.

120. Heer, T.; Garcia-Morchon, O.; Hummen, R.; Keoh, S.L.; Kumar, S.S.; Wehrle, K. Security Challenges in the IP-based Internet of Things. Wireless Personal Communications 2011, 61, 527–542.

121. Gan, G.; Lu, Z.; Jiang, J. Internet of Things Security Analysis.; IEEE, 2011; pp. 1–4.

122. Katagi, M.; Moriai, S. Lightweight cryptography for the internet of things. Sony Corporation 2008, 7–10.

123. Babar, S.; Stango, A.; Prasad, N.; Sen, J.; Prasad, R. Proposed embedded security framework for

Internet of Things (IoT).; IEEE, 2011; pp. 1–5.

124. Borgohain, T.; Kumar, U.; Sanyal, S. Survey of Security and Privacy Issues of Internet of Things. CoRR 2015, abs/1501.02211.

125. Roman, R.; Najera, P.; Lopez, J. Securing the Internet of Things. Computer 2011, 44, 51–58.

126. Mukherjee, A. Physical-Layer Security in the Internet of Things: Sensing and Communication Confidentiality Under Resource Constraints. Proceedings of the IEEE 2015, 103, 1747–1761.

127. Ning, H.; Liu, H.; Yang, L.T. Cyberentity Security in the Internet of Things. Computer 2013, 46, 46–53.

128. Kothmayr, T.; Schmitt, C.; Hu, W.; Brunig, M.; Carle, G. A DTLS based end-to-end security architecture for the Internet of Things with two-way authentication.; IEEE, 2012; pp. 956–963.

129. Raza, S.; Shafagh, H.; Hewage, K.; Hummen, R.; Voigt, T. Lithe: Lightweight secure CoAP for the internet of things. Sensors Journal, IEEE 2013, 13, 3711–3720.

130. Li, F.; Xiong, P. Practical Secure Communication for Integrating Wireless Sensor Networks Into the Internet of Things. IEEE Sensors Journal 2013, 13, 3677–3684.

131. Sethi, M.; Kortoci, P.; Di Francesco, M.; Aura, T. Secure and low-power authentication for resource-constrained devices.; IEEE, 2015; pp. 30–36.

132. Marques, G. Ambient Assisted Living and Internet of Things. In Harnessing the Internet of Everything (IoE) for Accelerated Innovation Opportunities; Cardoso, P.J.S., Monteiro, J., Semião, J., Rodrigues, J.M.F., Eds.; IGI Global: Hershey, PA, USA, 2019; pp. 100–115 ISBN 978-1-5225-7332-6.

133. Royakkers, L.; Timmer, J.; Kool, L.; van Est, R. Societal and ethical issues of digitization. Ethics and Information Technology 2018, 20, 127–142.

134. Shahraki, A.; Haugen, O. Social ethics in Internet of Things: An outline and review. In Proceedings of the 2018 IEEE Industrial Cyber-Physical Systems (ICPS); IEEE: St. Petersburg, 2018; pp. 509–516.

135. Iyengar, A.; Kundu, A.; Pallis, G. Healthcare Informatics and Privacy. IEEE Internet Computing 2018, 22, 29–31.

136. Ma, X.; Wang, Z.; Zhou, S.; Wen, H.; Zhang, Y. Intelligent Healthcare Systems Assisted by Data Analytics and Mobile Computing. Wireless Communications and Mobile Computing 2018, 2018, 1–16.

137. Sodhro, A.H.; Luo, Z.; Sangaiah, A.K.; Baik, S.W. Mobile edge computing based QoS optimization in medical healthcare applications. International Journal of Information Management 2019, 45, 308–318.

138. Enhanced Living Environments: Algorithms, Architectures, Platforms, and Systems; Ganchev, I., Garcia, N.M., Dobre, C., Mavromoustakis, C.X., Goleva, R., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, 2019; Vol. 11369; ISBN 978-3-030-10751-2.

139. Ambient assisted living and enhanced living environments: principles, technologies and control; Mavromoustakis, C.X., Garcia, N.M., Goleva, R.I., Mastorakis, G., Dobre, C., Eds.; Butterworth-Heinemann: Amsterdam ; Boston, 2017; ISBN 978-0-12-805195-5.

140. Nuno, P.; Pedro, A.; Joaquim, V.; Dias, da C.M. Evaluation of a ubiquitous and interoperable computerised system for remote monitoring of ambulatory post-operative pain: A randomised controlled trial. Technology and Health Care 2014, 63–75.

141. Pombo, N.; Garcia, N.M. ubiSleep: An ubiquitous sensor system for sleep monitoring. In Proceedings of the 2016 IEEE 12th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob); IEEE: New York, NY, 2016; pp. 1–4.

142. Marques, G.; Garcia, N.; Pombo, N. A Survey on IoT: Architectures, Elements, Applications, QoS, Platforms and Security Concepts. In Advances in Mobile Cloud Computing and Big Data in the 5G Era; Mavromoustakis, C.X., Mastorakis, G., Dobre, C., Eds.; Springer International Publishing: Cham, 2017; Vol. 22, pp. 115–130 ISBN 978-3-319-45143-5.

143. Pires, I.M.; Garcia, N.M.; Pombo, N.; Flórez-Revuelta, F.; Rodríguez, N.D. Validation Techniques for Sensor Data in Mobile Health Applications. Journal of Sensors 2016, 2016, 1–9.

Chapter 3

A System Based on the Internet of Things for Real-time Particle Monitoring in Buildings

This chapter presents an IoT architecture for PM real-time supervision is presented in this chapter. The proposed architecture is based on open-source technologies with several advantages such as its modularity, scalability, low-cost, and easy installation. Furthermore, this method incorporates a web Framework for data consulting, analysis and notifications.

The following article presents the Chapter 3.

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Article

A System Based on the Internet of Things for Real-time Particle Monitoring in Buildings

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Abstract: Occupational health can be strongly influenced by the indoor environment as people spend 90% of their time indoors. Although indoor air quality (IAQ) is not typically monitored, IAQ parameters could be in many instances very different from those defined as healthy values. Particulate matter (PM), a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air, is considered the pollutant that affects more people. The most health-damaging particles are the ≤PM_{10} (diameter of 10 microns or less), which can penetrate and lodge deep inside the lungs, contributing to the risk of developing cardiovascular and respiratory diseases, as well as of lung cancer. This paper presents an Internet of Things (IoT) system for real-time PM monitoring named iDust. This system is based on a WEMOS D1 mini microcontroller and a PMS5003 PM sensor that incorporates scattering principle to measure the value of particles suspended in the air (PM_{10}, $PM_{2.5}$, and $PM_{1.0}$). Through a Web dashboard for data visualization and remote notifications, the building manager can plan interventions for enhanced IAQ and ambient assisted living (AAL). Compared to other solutions the iDust is based on open-source technologies, providing a total Wi-Fi system, with several advantages such as its modularity, scalability, low cost, and easy installation. The results obtained are very promising, representing a meaningful tool on the contribution to IAQ and occupational health.

Keywords: indoor air quality (IAQ); healthy buildings; occupational health; particulate matter (PM); real-time monitoring; internet of things (IoT)

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1. Introduction

People spend about 90% of their time in indoor environments, and especially the elderly population and newborns, who are the most susceptible to indoor pollution, may spend all their time in indoor environments. Thus, indoor air quality (IAQ) is the main descriptor of personal exposure to pollutants [1].

Poor IAQ is assumed as a challenge of greatest significance which particularly affects the poorest and unprotected individuals worldwide who are most defenseless introducing itself as a significant issue for world well-being, that can be compared with others such as tobacco use or sexually transmitted diseases [2]. The U.S. Environmental Protection Agency (EPA), responsible for indoor and outdoor air quality regulation in the USA, considers that indoor levels of pollutants might be up to 100 times higher than outdoor air pollutant levels and positioned poor air quality as one of the most important five environmental problems to the general well-being [3].

In 2050, 20% of the world's population will be age 60 or above [4], which will result in an increase in diseases, health care costs, shortage of caretakers dependency and brutal social impact. In fact, 87% of the people prefer to stay in their homes and bear the remarkable cost of nursing care [5], which makes the study of ambient assisted living (AAL) architectures undoubtedly a topic of great relevance given the aging of the world population. AAL technologies are designed to meet the needs of the aging population to maintain their independence as long as possible.

On the one hand, enhancements in networks, sensors, and embedded systems have made possible the provision of real-time monitoring and personalized healthcare systems to individuals that they can now use in their living environments. In another hand, these uninterrupted technological improvements make possible the development of intelligent cyber-physical systems for enhanced living environments and occupational health. Although there is a lot of challenges in the design and implementation of an effective AAL system such as information architecture, interaction design, human-computer interaction, ergonomics, usability and accessibility [6], there are also social and ethical problems like the acceptance by the older adults and the privacy and confidentiality that should be a requirement of all AAL devices. In fact, it is also important to ensure that technology does not replace the human care but rather should be a remarkable compliment.

IoT is a paradigm where objects are connected to the internet and support sensing capabilities. Tendentiously IoT devices should be ubiquitous, context-aware and enable ambient intelligence features closely related to AAL. IoT is a suitable approach to build health care systems; technology advancements allow one to define new advanced tools and also allow real-time health monitoring platforms for decision making in the treatment of many diseases. IoT offers a perfect platform for ubiquitous healthcare, using, for example, wearable sensors for uploading data to servers and smartphones for communication, along with Bluetooth for interfacing sensors measuring physiological parameters [7]. The IoT is also used for real-time transmission of physical information. In 2009 some projects for remote health care program design based on IoT that can improve the intelligence of information collection and process already existed, which promoted IoT applications in the medical industry [8]. Despite the potential of the IoT paradigm and technologies for health systems today many challenges to be overcome still exist. The direction and impact of the IoT on the economy are not yet clear, there are barriers to the immediate and ubiquitous adoption of IoT products, services, and solutions which may sound feasible for implementation, but the timing might be too early [9].

An IAQ evaluation system helps in the monitoring and decision making at real-time interventions to increase occupational health. Local and distributed assessment of chemical concentrations is significant for safety (e.g., gas spills detection and pollution monitoring) and security applications, as well as to control heating, ventilation, and air conditioning (HVAC) systems for energy efficiency [10]. In fact, the IAQ measured in the manufactured environment provides a consistent stream of data for reliable management of building automation systems and provides a platform for informed decision-making [11].

In most situations, easy interventions that can be carried out by homeowners and building administrators can deliver remarkable positive effects on IAQ, for example, the avoidance of smoking inside and the utilization of natural ventilation are critical practices that should be instructed to families through instructive projects that address the IAQ [12].

Numerous IoT architectures for IAQ supervision which support open-source technologies for data processing, collection, and transmission that offers mobile computing architectures for real-time data accessibility are proposed in [13–22]. Particularly, IAQ monitoring is a trending topic for which some other low-cost and open-source monitoring systems that had been developed [23–27]. A brief summary of these studies is presented in Table 1.

This paper aims to present iDust, a solution for real-time monitoring based on an IoT architecture. To create a low-cost system for PM, the authors selected a PMS5003 sensor that incorporates scattering principle to measure the value of particles suspended in the air with a diameter of 10 microns or less ($\leq PM_{10}$), 2.5 microns or less ($\leq PM_{2.5}$) and 1.0 microns or less ($\leq PM_{1.0}$).

Table 1. A short summary of similar type of research on IoT platform for real-time indoor air quality monitoring.

	MCU	Sensors	Architecture	Low Cost	Open-Source	Connectivity	Data Access	Easy Installation
D. Lohani and D. Acharya [23]	Arduino UNO, ESP8266	Temperature, Relative Humidity, CO_2	IoT	√	√	Wi-Fi, BLE	Mobile	×
P. Srivatsa and A. Pandhare [24]	Raspberry Pi	CO_2	WSN/IoT	√	√	Wi-Fi	Web	×
F. Salamone et al. [25]	Arduino UNO	CO_2	WSN	√	√	ZigBee	×	×
S. Bhattacharya et al. [26]	Waspmote	CO, CO_2, PM, Temperature, Relative Humidity	WSN	×	√	ZigBee	Desktop	×
F. Salamone et al. [27]	Arduino UNO	Temperature, Relative Humidity, CO_2, Ligth, Air velocity	IoT	√	√	ZigBee / BLE	Mobile	×

MCU: microcontroller; √: apply; ×: not apply.

The paper is structured as follows: after this Introduction (Section 1), Section 2 introduces in detail the PM exposure effects in health; Section 3 is concerned to the methods and materials used in the implementation of the sensor system; Section 4 demonstrates the system operation and experimental results; Finally, the conclusions are presented in Section 5.

2. Particulate Matter's Effects on Health

PM can be defined as a multifaceted combination of solid and liquefied biological and mineral material particles suspended in the air and is therefore mentioned by several researchers as the pollutant that influences more individuals [28,29]. PM include dust, dirt, soot, smoke, and liquid droplets that are capable of penetrating the lower airways of humans and can cause possible negative health effects. In developing countries, indoor exposure to PM increases the risk of acute lower respiratory infections and associated mortality among young children, but also represent a major risk factor for cardiovascular disease, chronic obstructive pulmonary disease and lung cancer among adults. Typically there are strong similarities between airborne particulate matter sampled in cities in developed countries across the world [30].

Already in 1987, the US EPA redefined the National Ambient Air Quality Standard (NAAQS) for particles based on particulate matter smaller than PM_{10} [31]. Environmental tobacco smoke is a major contributor to indoor air concentrations and human exposures to particles [32]. The World Health Organization (WHO) considers as threshold values for PM_{10} and $PM_{2.5}$ 20 and 10 $\mu g \cdot m^{-3}$ (annual mean) or 25 and 50 $\mu g \cdot m^{-3}$ (24-h mean), respectively [33]. There is increasing evidence of PM-related cardiovascular health effects, as well as a pathophysiological interconnection that links PM exposure with cardiopulmonary morbidity and mortality [34,35].

For routine monitoring for regulatory purposes, ambient PM is quantified via PM_{10} and $PM_{2.5}$ metrics. PM_{10} and $PM_{2.5}$ are defined as the mass concentrations of particles within a size fraction collected by automatic systems with inlet transmission curves that respect international sampling standards related to 'inhalable' and 'respirable' particles, respectively. Generally, PM_{10} (particles equal to and less than 10 microns in aerodynamic diameter) are not deposited in the lungs. $PM_{10-2.5}$ (commonly defined as particles with an aerodynamic diameter greater than 2.5 microns, but equal to or less than a nominal 10 microns) are also known as coarse fraction particles. Particles smaller than 1 micron in diameter are represented by $PM_{1.0}$. "Ultrafine" particles (UFP) are generally defined as the particles less than 0.1 microns (100 nm) in size (Figure 1) [36].

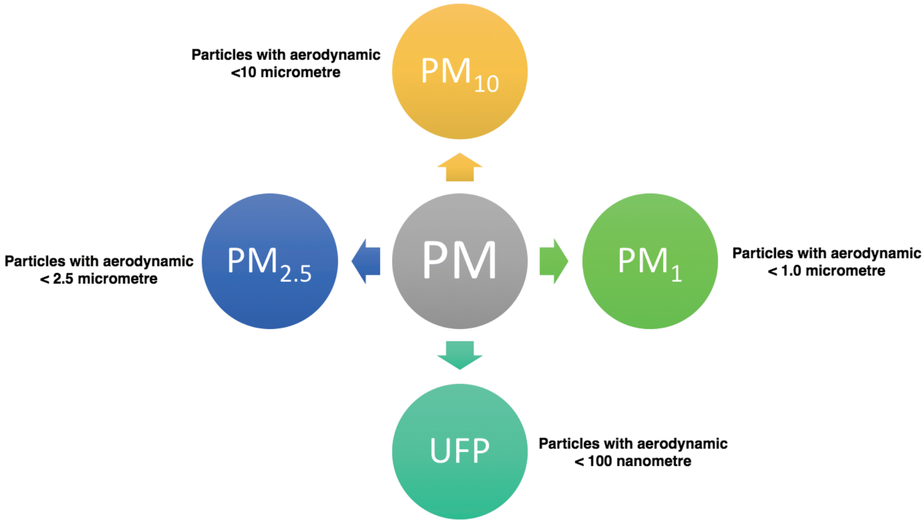


Figure 1. PM types.

Today the UFP concentrations are not monitored routinely, and enhanced measurement is necessary as it would support the development of more powerful epidemiological studies [37,38].

$PM_{2.5}$ is associated with all-cause, lung cancer, and cardiopulmonary mortality and each 10 $\mu g \cdot m^{-3}$ elevation in $PM_{2.5}$ was associated with approximately a 4%, 6%, and 8% increased risk of all-cause, cardiopulmonary and lung cancer mortality, respectively [39].

Epidemiological studies point to a consistent association between particulate air pollution and not only exacerbations of illness in people with respiratory disease, but also rises in the number of deaths from cardiovascular and respiratory disease among older people [40]. As referred by [41] particle pollutants are estimated to cause more than 500,000 deaths annually, and the adverse effects of ultrafine air particles are linked to their ability to gain access to the lung and systemic circulation, where toxic components lead to tissue damage and inflammation. PM measurements can be intensely predisposed to mechanically produced, soil-derived particles, which could not be linked with unfavorable health effects so IAQ monitoring should include PM concentration [42].

The allergist–clinical immunologist should be strongly aware that both gaseous and particulate outdoor pollutants might augment or improve the fundamental pathophysiology of both the upper and lower airways [43].

Observed health effects of PM include increased respiratory symptoms, decreased lung function, increased hospitalizations, other healthcare visits for respiratory and cardiovascular disease, increased respiratory morbidity as measured by absenteeism from work and school or other restrictions in activity and increased cardiopulmonary disease mortality as referred by [44]. Through iDust, the medical decision and diagnosis can be supported by historical environment's data of PM exposure where the patient lives serving as a powerful tool for real-time healthcare monitoring and decision making. A study suggesting that the acidity of particles is not as important in associations with daily mortality as the mass concentrations of particles is presented by [45]. Consequently, the iDust focuses on the real-time monitoring of the concentrations of particles for enhanced occupational health.

PM exposure is ubiquitous and while there is no defined and studied "safe" level, behavioral modification strategies may contribute to better overall health. It's necessary to enable policymakers, after weighing the economic impact, to establish enhanced legislation that limits PM exposure. There are natural PM sources such as volcanoes, forest fires that are unavoidable. However, some others sources are avoidable and several practices that can be administered keeping in mind the end goal to diminish PM exposure and decrease the morbidity and mortality [46].

In indoor environments, the health effects of inhaled biological particles can be significant, as a large variety of biological materials are present. One of the primary constituents of the smoke is respirable particles. These are aerosols with a small enough diameter to enter and remain in the lung, many are around 6–7 μm, or less in diameter [12]. Research that uses a sample of personalities conducted by [47,48] concludes that in general, the PM exposure in outdoor environments is greater than in indoor living environments, particularly in the daytime. Usually, the PM well-being effects of outdoor environments are reasonably well considered than those related to indoor living environments [49].

Tobacco smoke particles measure from 0.1 to 1.5 μm [50]. Research conducted by [51] concludes that a smoking one pack of cigarettes a day causes approximately 20 $\mu g \cdot m^{-3}$ to 24 h indoor concentrations and that short-term concentration of 500–1000 $\mu g \cdot m^{-3}$ are probable once the tobacco is lit. Several chronic exposure research studies suggest relatively general vulnerability to aggregated consequences of long-term $PM_{2.5}$ exposure and consequential population average loss of life expectancy in extremely contaminated environments [52].

3. Materials and Methods

Taking into account all the health negative effects of PM exposure described above, the authors had the objective of developing an automatic PM monitoring system called iDust. This system is intended to be a healthcare real-time monitoring system and decision-making tool. The solution is composed of a hardware prototype for ambient data collection and a Web portal developer in .NET for data consulting. The iDust is based on open-source technologies and is a totally Wi-Fi system, with several advantages compared to existing systems, such as its modularity, scalability, low-cost and easy installation. The data is uploading to the SQL SERVER database using .NET Web services (Figure 2). This system is based on a WEMOS D1 mini microcontroller with built-in Wi-Fi communication technology as communication and processing unit and incorporates a PMS5003 sensor as sensing unit.

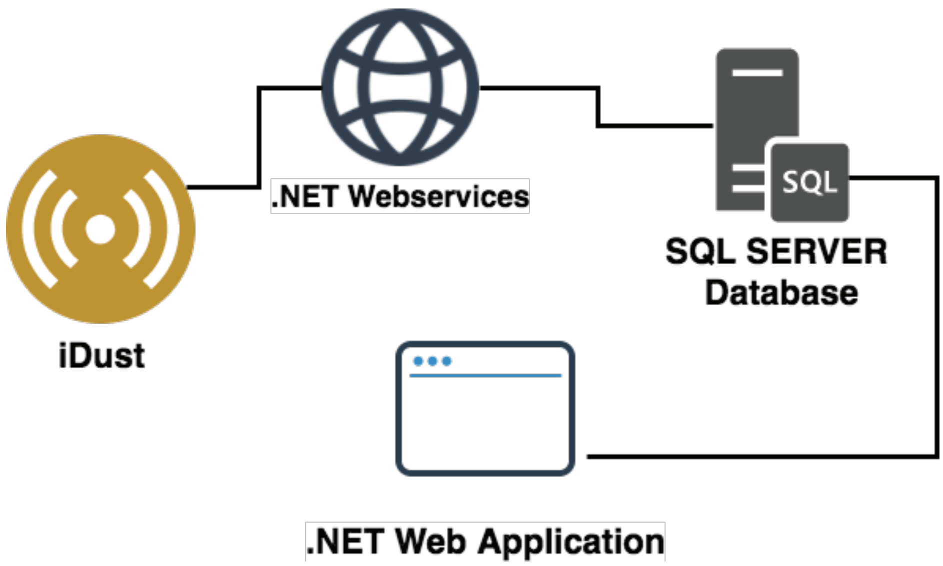


Figure 2. iDust system architecture.

The iDust is a software/hardware solution for real-time IAQ supervising that acknowledges the end user, as the building supervisor for example, to real-time monitoring the PM exposure. The solution is based on the Arduino platform using the ARDUINO IDE for software development and the WEMOS D1 mini as a microcontroller. The parameters are monitored using the iDust prototype, which collects data that is stored in a SQL SERVER database using Web services developed in .NET. The end user can access the data from the Web portal developed using ASP.NET. After the user authentication, it is possible to access the real-time PM exposure data. The data collected is presented in a dashboard in both numeric values or chart form. Furthermore, the Web Application is responsible for saving the history of the PM exposure data. By offering a chronological history of the PM exposure data, this solution assists the builder manager to analyze the IAQ behavior accurately. This functionality is exceptionally significant on behalf of determining on conceivable interventions to increase the IAQ in the building. Additionally, this feature might stand particularly significant for therapeutic assessment and diagnosis support since the clinical team might analyze the environment where the patient resides. The Web Application remains additionally prepared with a powerful notification manager that alerts the user when a specific parameter outdoes the maximum rate. iDust is a low-cost, reliable system that can be easily configured and installed by the average user. For this, we selected a low cost but very reliable PM sensor and a microcontroller with native Wi-Fi support. This system consists of two components: a WEMOS D1 mini microcontroller (WEMOS Electronics, China) and a PMS5003 PM sensor (Plantower, City, State Abbrev if USA, Country), which incorporates scattering principle to measure the value of particles suspended in the air with a diameter of 10 microns or less (≤PM_{10}), 2.5 microns or less (≤$PM_{2.5}$) and 1.0 microns or less (≤$PM_{1.0}$) (Figure 3).

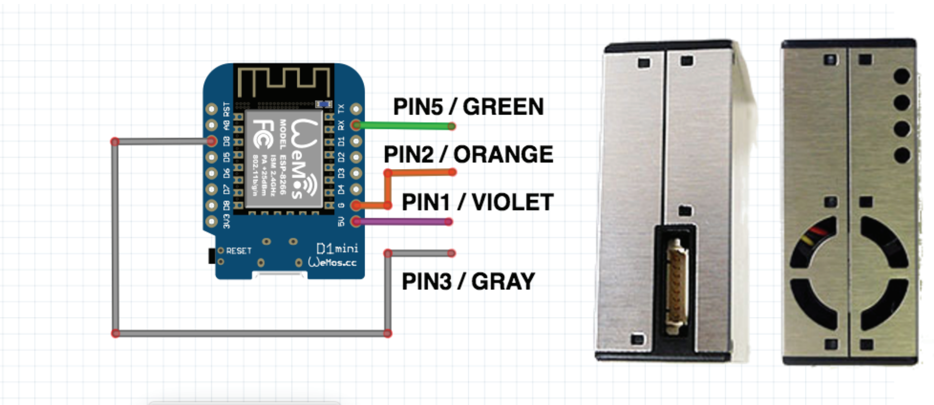


Figure 3. iDust Connection Diagram.

A brief introduction of each component used is shown below

- WEMOS D1—This device incorporates an ESP8266 Wi-Fi chip with integrated antenna switches, RF balun, power amplifier, low noise receive amplifier, filters, and power management modules. It supports 802.11 b/g/n protocols, Wi-Fi 2.4 GHz, support WPA/WPA2, has an integrated low power 32-bit MCU, an integrated 10-bit ADC, has a standby power consumption of <1.0 mW (DTIM3) and can operate at temperature range −40~125 °C. The WEMOS D1 that offers 11/1 digital input/output pins, 1 analogue input, and a micro USB interface for development and power supply. It is totally supported by Arduino IDE platform, has an 80/160 MHZ CPU clock, 4 MB Flash, a 3.3 V operating voltage, a compact dimension of 34.2 mm × 25.6 mm, and a weight of 10 g.
- PMS 5003—this PM sensor was developed with special attention to its mechanical design which prevents dust accumulation where the laser and diode are mounted. Regarding electrical and electronic components, the PMS5003 incorporates Cypress CY8C4245 CPU, an ARM Cortex-M0 running at 48 Mhz with dedicated ADC. The PMS5003 applies the scattering principle to measure the value of particles suspended in the air with a diameter of 10 microns or less (≤PM_{10}), 2.5 microns or less (≤$PM_{2.5}$) and 1.0 microns or less (≤$PM_{1.0}$). This PM sensor has a standby power consumption of <0.2 mW and can operate in a temperature range of −10~60 °C.

4. Results and Discussion

In Portugal, most buildings have natural ventilation. The type of dwelling, construction, heating, and ventilation all have a bearing on the extent to which air permeability changes. It is estimated that two-thirds of commercial/services buildings, with natural ventilation, are extremely airtight, and the remaining third tend to be leakier.

For testing purposes, two laboratories of a Portuguese university were on-site monitored, and two iDust sensors modules (SM1 and SM2) were used. Figure 4 represents the experiment done by the authors of the implementation of the iDust system. As in the most buildings, the two spaces monitored are naturally ventilated, without any dedicated ventilation slots on the facades. The indoor air is heated and recirculated by two typical air-water fan-coils from the heating system, and the air exchange is achieved through infiltrations and opening windows controlled by the occupants. Once the outdoor air is only used to provide ventilation or to cool normally when the occupants feel the bad or irritating smell, the IAQ is normally poor.

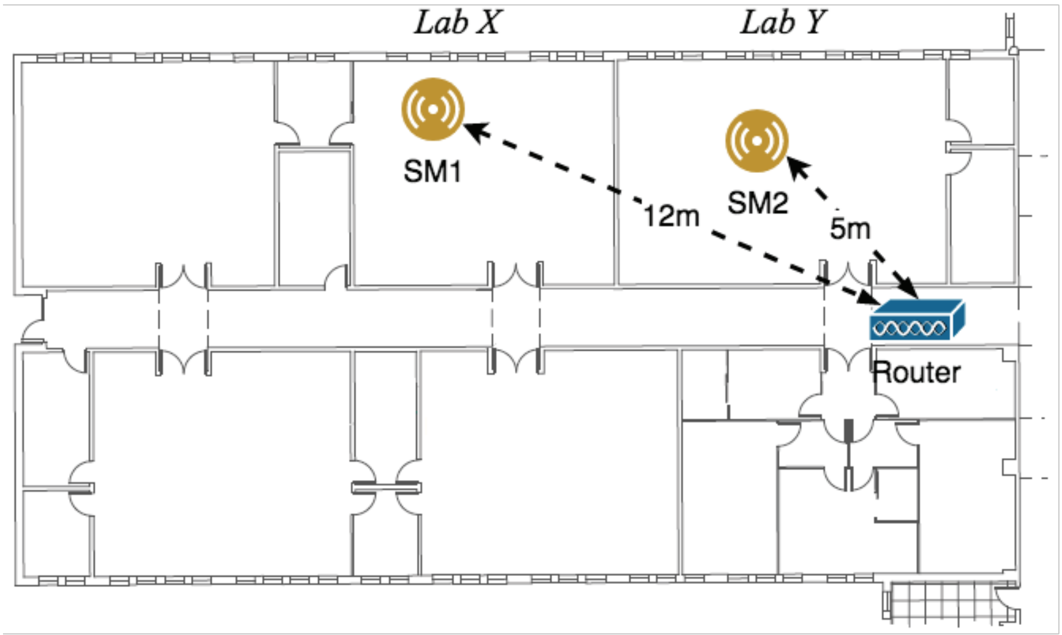
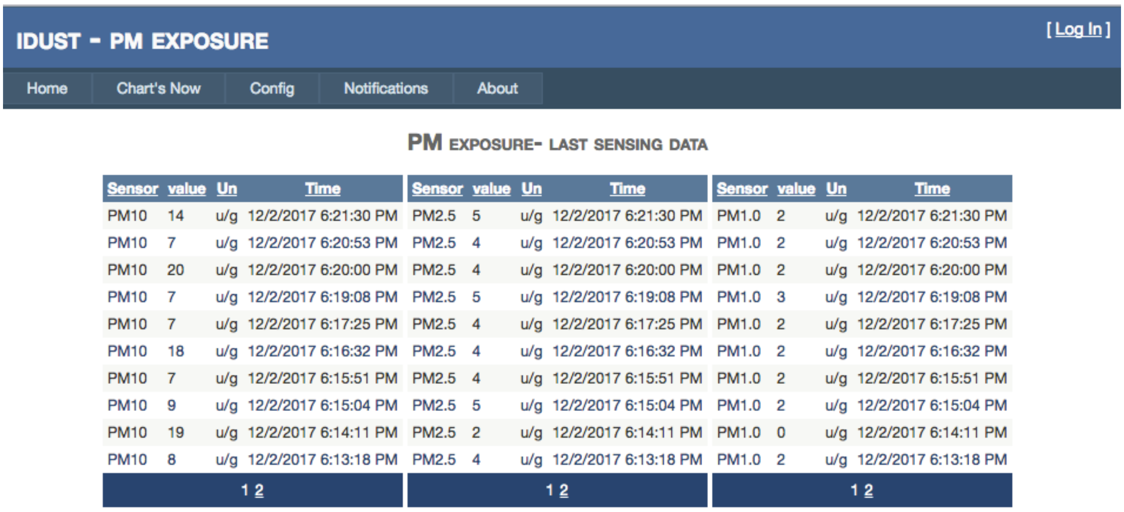


Figure 4. iDust installation schema.

All modules are powered by the power grid using a 230V-5V AC-DC 2A power supply. PM exposure data were collected for two months which showed that under certain conditions air quality values are significantly lower than those considered healthy for standards. The tests conducted show the system capability to analyze in real-time the IAQ, the potential to planning interventions to ensure safe healthy and comfortable conditions, but also to identify multiple situations or habits that affect the IAQ negatively.

Using the Web application, the end user can easily access the PM exposure data in real-time. The Web Application lets the end-user to keep the parameters history as is showed in Figure 5. This functionally provides precise and detailed access to the PM exposure behavior.

A sample of the graphics with the results obtained in the experiments collected by iDust is shown below (Figure 6). It should be noted that the graphs displayed the results obtained in the monitored rooms with induced simulations using tobacco smoke.



Sensor	value	Un	Time	Sensor	value	Un	Time	Sensor	value	Un	Time
PM10	14	u/g	12/2/2017 6:21:30 PM	PM2.5	5	u/g	12/2/2017 6:21:30 PM	PM1.0	2	u/g	12/2/2017 6:21:30 PM
PM10	7	u/g	12/2/2017 6:20:53 PM	PM2.5	4	u/g	12/2/2017 6:20:53 PM	PM1.0	2	u/g	12/2/2017 6:20:53 PM
PM10	20	u/g	12/2/2017 6:20:00 PM	PM2.5	4	u/g	12/2/2017 6:20:00 PM	PM1.0	2	u/g	12/2/2017 6:20:00 PM
PM10	7	u/g	12/2/2017 6:19:08 PM	PM2.5	5	u/g	12/2/2017 6:19:08 PM	PM1.0	3	u/g	12/2/2017 6:19:08 PM
PM10	7	u/g	12/2/2017 6:17:25 PM	PM2.5	4	u/g	12/2/2017 6:17:25 PM	PM1.0	2	u/g	12/2/2017 6:17:25 PM
PM10	18	u/g	12/2/2017 6:16:32 PM	PM2.5	4	u/g	12/2/2017 6:16:32 PM	PM1.0	2	u/g	12/2/2017 6:16:32 PM
PM10	7	u/g	12/2/2017 6:15:51 PM	PM2.5	4	u/g	12/2/2017 6:15:51 PM	PM1.0	2	u/g	12/2/2017 6:15:51 PM
PM10	9	u/g	12/2/2017 6:15:04 PM	PM2.5	5	u/g	12/2/2017 6:15:04 PM	PM1.0	2	u/g	12/2/2017 6:15:04 PM
PM10	19	u/g	12/2/2017 6:14:11 PM	PM2.5	2	u/g	12/2/2017 6:14:11 PM	PM1.0	0	u/g	12/2/2017 6:14:11 PM
PM10	8	u/g	12/2/2017 6:13:18 PM	PM2.5	4	u/g	12/2/2017 6:13:18 PM	PM1.0	2	u/g	12/2/2017 6:13:18 PM
1 2				1 2				1 2			

Figure 5. iDust Web application.

The iDust is also equipped with a powerful alerts manager that notifies the user when the air quality is poor. Based on well-studied values, the maximum and minimum health quality values are predefined by the system, but the user can also change these values to specific proposes. When a value exceeds the defined threshold, the user will be notified by e-mail in real-time. Other notifications are planned as future work such as Short Message System (SMS, Figure 7).

The data collected by the system is analyzed before being inserted into the database if the data exceeds the parameterized limits the user receives are notified, and the email is triggered. Consecutively the user can act in real-time ensuring good ventilation of the indoor environment.

The graphical display of the air quality data allows a greater perception regarding the behavior of the monitored parameters than the numerical display format. On the other hand, the Web application also allows a more precise analysis of the detailed temporal evolution. Thus, the system is a powerful tool for analyzing air quality consumption and to support decision making on possible interventions to improve a healthy and more productive indoor environment.

The iDust has advantages both in ease of installation and configuration due to the use of wireless technology but also due to its small size (about 5.5 cm × 4.5 cm × 4.5 cm depth), compared to other systems and also have a Web Application to provide relevant information anytime and anywhere to the users.

Compared to similar solutions the iDust provides a web platform for data consulting and notifications. It is relevant to support the planning of interventions on the building and to be shared with a medical team indoor to support diagnostics. In fact, we spend about 90% of our lives in indoor environments, so it is necessary to monitor the PM level to plan changes of habits and even interventions in the ventilation to provide a healthier and productive living environment. This system makes a significant contribution compared to existing air quality monitoring systems due to its low cost of construction, installation, modularity, scalability and easy access to monitoring data in real-time through the web application.

The iDust system uses the ESP8266 for both processing and Internet connectivity, which offers several advantages regarding reducing the cost of the system, but also improves processing power because the ESP8266 has an 80 MHZ CPU, while the Arduino UNO has a 16 MHZ CPU. The use of the ESP8266 has another important feature that provides to the end user an easy configuration of the Wi-Fi network to which iDust will be connected. The ESP8266 is by default a Wi-Fi client, but in the case, it is unable to connect to the Wi-Fi network, or if there are no wireless networks available, the ESP8266 will turn to hotspot mode and will create a Wi-Fi network with an SSID "IAQ-iDust." At this point, the end-user can connect to this Wi-Fi network which permits the configuration of the Wi-Fi network to which the iDust is going to connect through the introduction of the network SSID and password using a web form (Figure 8).

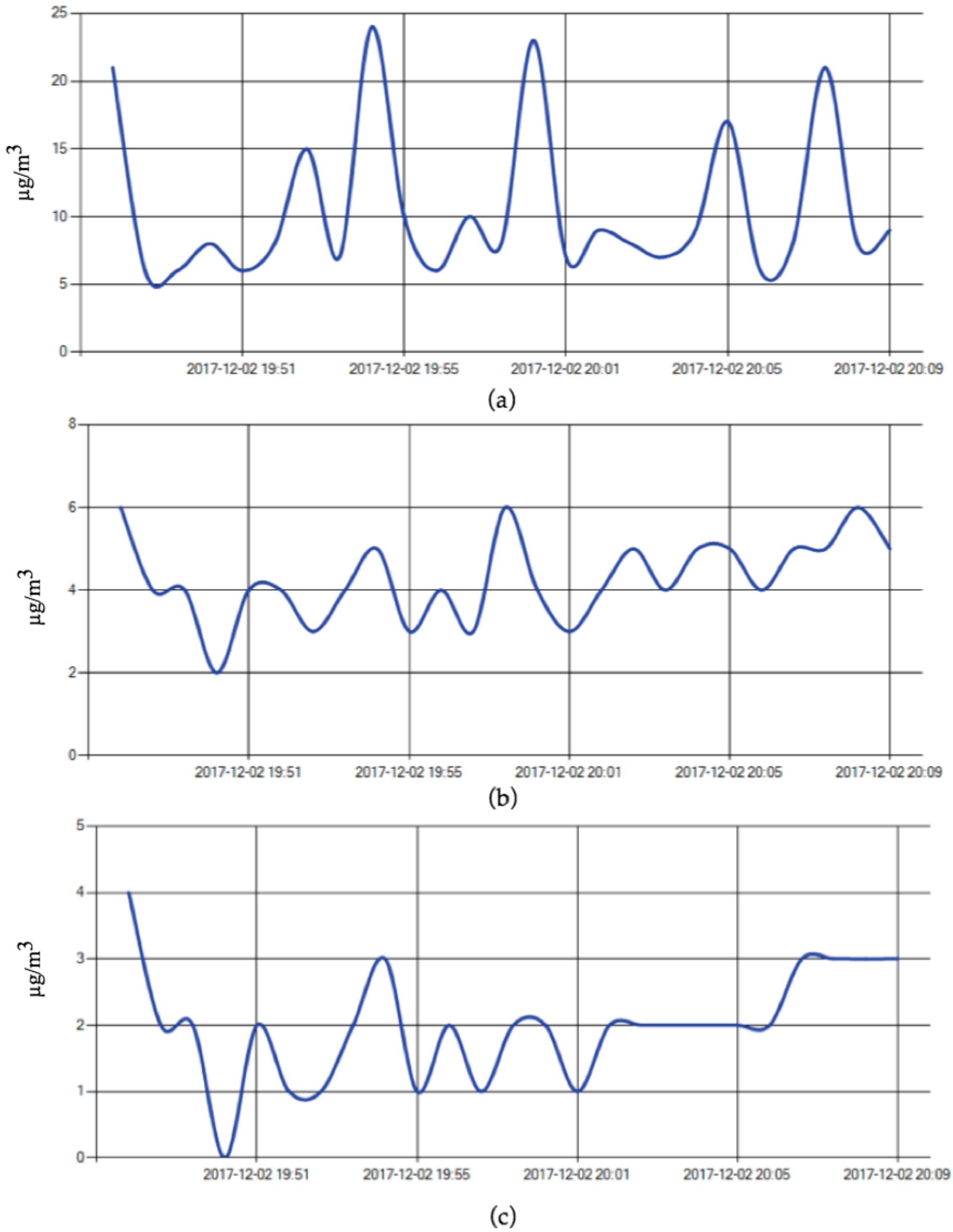


Figure 6. Results of particulate matter concentrations obtained in the experiments conducted in a real environment: (**a**) PM10) (µg/m^3); (**b**) PM2.5 (µg/m^3); (**c**) PM1.0 (µg/m^3).

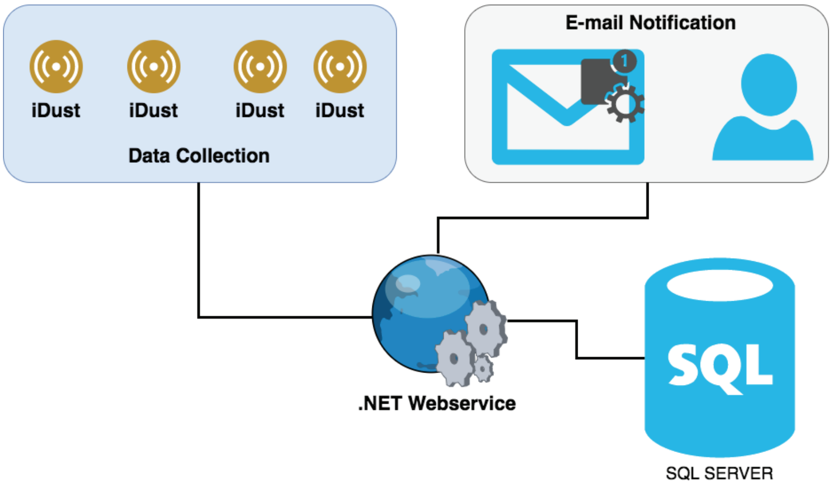


Figure 7. iDust Notification Architecture.

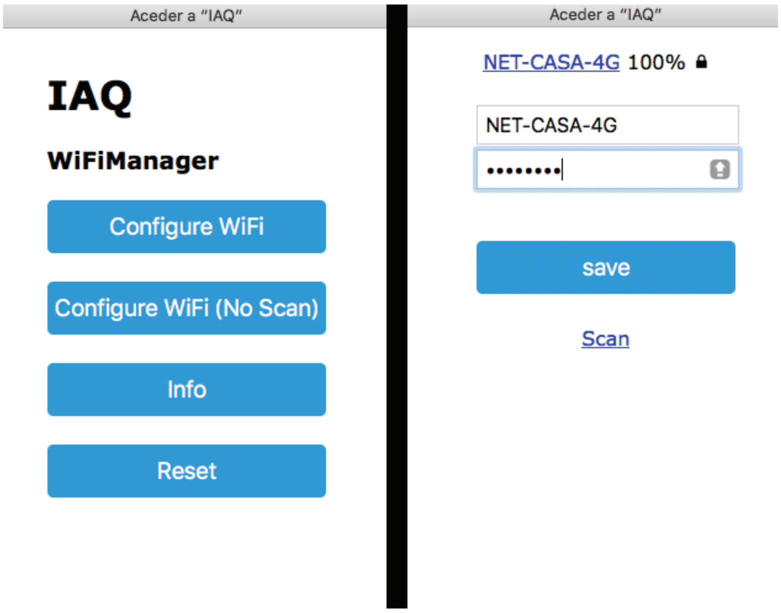


Figure 8. iDust Wi-Fi configuration.

These features make the iDust an easy to install product which follows the original paradigm of IoT solutions. In contrast of the majority of the IAQ monitoring solutions that must be installed by specialized professionals, the iDust can be configured by the end user requiring only a smartphone or another gadget with Wi-Fi connectivity, thus contributing to the low-cost aim of the iDust solution. Another great advantage of this system is the notification system that allows users to act in real-time to significantly improve indoor air quality through the ventilation or deactivation of pollutant equipment.

Finally, the IoT architecture enables the scalability of the system providing flexibility and expandability as the user can start with a few stations for data collection and add more stations as the needs and complexity of the indoor environment.

Improvements to the system hardware and software are planned to make it much more appropriate for specific purposes such as hospitals, schools, and offices. The system has advantages both in installation and configuration, due to the use of wireless technology for communications, but also because it was developed for to be compatible with all domestic house devices and not only for smart houses or high-tech houses.

The iDust not only provide a detailed PM exposure data in a table or graphic form but also provide real-time notifications for acting in real-time (Figure 9).

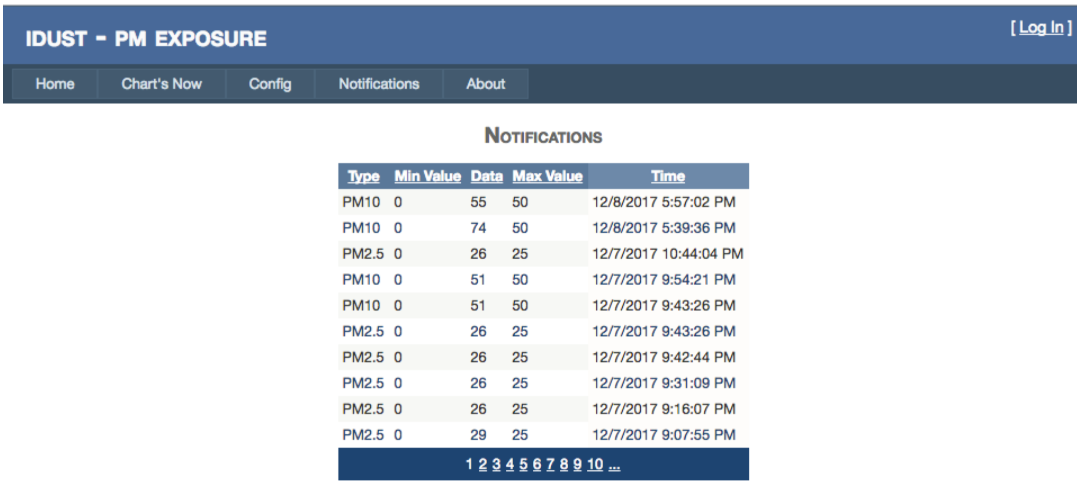


Figure 9. iDust Notifications.

It is imperative to control the PM exposure effectively and we believe that the first step is to perform real-time monitoring to perceive its variation in real-time and to plan interventions for its reduction.

IoT architectures and AAL technologies not only will remain side by side adding scientific improvements to enhanced living environments but also lower the cost of ubiquitous solutions. Despite the many technologic advances some difficulties in the construction of IoT solutions, several issues remain, mostly related to the privacy, data confidentiality, and security of such systems. Despite all the advantages of healthcare systems based on IoT architectures, several open issues continue to exist, such as availability, reliability, mobility, performance, scalability, and interoperability. Any proposed system should find ways to respond to these problems. It is extremely important to repeat that this kind of healthcare system should be used to support medical treatments as an important complement to medical supervision.

5. Conclusions

PM is related to numerous serious health problems. This paper presented iDust, a real-time PM exposure monitoring system and decision-making tool for enhanced healthcare based on an IoT architecture It was developed using open-source technologies and low-cost sensors. The results obtained are very promising, as the solution could be used to support the building manager for the appropriate operation and maintenance to deliver not just a safe but also a healthful workplace for enhanced occupational health. In the one hand, the PM exposure information can be particularly valuable to offer support to a medical examination by clinical professionals as the medical team might analyze the history of IAQ parameters of the ecosystem everywhere the patient lives and relate these records with his health complications. On the other hand, by monitoring IAQ, it is possible to perceive correctly the air quality conditions and if necessary, plan interventions to decrease the PM exposure levels.

The results of the experiments reveal that iDust system can provide an effective PM assessment to prevent exposure risk. In fact, the IAQ may be extremely different than what is expected of a quality living environment. Therefore, this system is a useful tool for monitoring the PM of the indoor air and aims to ensure the permanent categorization of PM. It was also possible to conclude that the occupants only perceive the poor conditions of air quality in extreme situations, so by using iDust, it is possible to detect and correct the problems at a very early stage.

As future work, the authors plan software and hardware improvements to adapt the system to specific cases such as hospitals, schools, and industry. It is also important to create new monitoring solutions with the objective to develop an ecosystem for IAQ as well as the enhancements in the Web Application to increase the data safety and privacy for accessibility to health professionals planning to support medical diagnostics. We believe that in the future, systems like this will contribute to enhanced living environments but also be an integral part of the daily human routine.

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Author Contributions: Gonçalo Marques and Rui Pitarma designed the study, developed the methodology, performed the analysis, and wrote the manuscript. Cristina Roque Ferreira revised the manuscript on medical issues.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Walsh, P.J.; Dudney, C.S.; Copenhaver, E.D. *Indoor Air Quality*; CRC Press: Boca Raton, FL, USA, 1983.
2. Bruce, N.; Perez-Padilla, R.; Albalak, R. Indoor Air Pollution in Developing Countries: A Major Environmental and Public Health Challenge; Bulletin of the World Health Organization: Geneva, Switzerland , 2000; Volume 78, pp. 1078–1092.
3. Seguel, J.M.; Merrill, R.; Seguel, D.; Campagna, A.C. Indoor Air Quality. *Am. J. Lifestyle Med.* **2016**, *11*, 284–295.
4. United Nations. World Population Ageing: 1950–2050. *Pop. Dev. Rev.* **2002**, *28*, 11–13.
5. Centers for Disease Control and Prevention (CDC). The State of Aging and Health in America 2007. Available online: https://www.cdc.gov/aging/pdf/saha_2007.pdf (accessed on 2 December 2017).
6. Koleva, P.; Tonchev, K.; Balabanov, G.; Manolova, A.; Poulkov, V. Challenges in designing and implementation of an effective Ambient Assisted Living system. In Proceedings of the 2015 12th International Conference on Telecommunication in Modern Satellite, Cable and Broadcasting Services (TELSIKS), Nis, Serbia, 4–17 Ocober 2015; pp. 305–308.
7. Gubbi, J.; Buyya, R.; Marusic, S.; Palaniswami, M. Internet of Things (IoT): A vision, architectural elements, and future directions. *Future Gener. Comput. Syst.* **2013**, *29*, 1645–1660.
8. Luo, J.; Chen, Y.; Tang, K.; Luo, J. Remote monitoring information system and its applications based on the Internet of Things. In Proceedings of the FBIE 2009 International Conference on Future BioMedical Information Engineering, 2009, Sanya, China, 13–14 December 2009; pp. 482–485.
9. Swan, M. Sensor Mania! The Internet of Things, Wearable Computing, Objective Metrics, and the Quantified Self 2.0. *J. Sens. Actuat. Netw.* **2012**, *1*, 217–253.
10. De Vito, S.; Fattoruso, G.; Liguoro, R.; Oliviero, A.; Massera, E.; Sansone, C.; Casola, V.; Di Francia, G. Cooperative 3D Air Quality Assessment with Wireless Chemical Sensing Networks. *Procedia Eng.* **2011**, *25*, 84–87.
11. Preethichandra, D.M.G. Design of a smart indoor air quality monitoring wireless sensor network for assisted living. In Proceedings of the 2013 IEEE International, Instrumentation and Measurement Technology Conference (I2MTC), Minneapolis, MN, USA, 6–9 May 2013; pp. 1306–1310.
12. Jones, A.P. Indoor air quality and health. *Atmos. Environ.* **1999**, *33*, 4535–4564.
13. Pitarma, R.; Marques, G.; Ferreira, B.R. Monitoring Indoor Air Quality for Enhanced Occupational Health. *J. Med. Syst.* **2017**, *41*, 23.
14. Marques, G.; Pitarma, R. Health informatics for indoor air quality monitoring. In Proceedings of the 2016 11th Iberian Conference on Information Systems and Technologies (CISTI), Las Palmas, Spain, 15–18 June 2016; pp. 1–6.
15. Pitarma, R.; Marques, G.; Caetano, F. Monitoring Indoor Air Quality to Improve Occupational Health. In *New Advances in Information Systems and Technologies*; Rocha, Á., Correia, A.M., Adeli, H., Reis, L.P., Teixeira, M.M., Eds.; Springer International Publishing: Basel, Switzerland, 2016; Volume 445, pp. 13–21.
16. Marques, G.; Pitarma, R. Smartphone Application for Enhanced Indoor Health Environments. *J. Inf. Syst. Eng. Manag.* **2016**, *4*, 9.
17. Marques, G.; Pitarma, R. Monitoring Health Factors in Indoor Living Environments Using Internet of Things. In *Recent Advances in Information Systems and Technologies*; Rocha, Á., Correia, A.M., Adeli, H.,

Reis, L.P., Costanzo, S., Eds.; Springer International Publishing: Basel, Switzerland, 2017; Volume 570, pp. 785–794.
18. Marques, G.; Pitarma, R. Monitoring and control of the indoor environment. In Proceedings of the 2017 12th Iberian Conference on Information Systems and Technologies (CISTI), Lisbon, Portugal, 14-17 June 2017; pp. 1–6.
19. Feria, F.; Parra, O.J.S.; Daza, B.S.R. Design of an Architecture for Medical Applications in IoT. In *Cooperative Design, Visualization, and Engineering*; Luo, Y., Ed.; Springer International Publishing: Basel, Switzerland, 2016; Volume 9929, pp. 263–270.
20. Ray, P.P. Internet of things for smart agriculture: Technologies, practices and future direction. *J. Ambient Intell. Smart Environ.* **2017**, *9*, 395–420.
21. Matz, J.R.; Wylie, S.; Kriesky, J. Participatory Air Monitoring in the Midst of Uncertainty: Residents' Experiences with the Speck Sensor. *Engag. Sci. Technol. Soc.* **2017**, *3*, 464.
22. Demuth, D.; Nuest, D.; Bröring, A.; Pebesma, E. The AirQuality SenseBox. In *EGU General Assembly Conference Abstracts*; Copernicus: Viena, Austria, 2013; Volume 15.
23. Lohani, D.; Acharya, D. Smartvent: A context aware iot system to measure indoor air quality and ventilation rate. In Proceedings of the 2016 17th IEEE International Conference on Mobile Data Management (MDM), Porto, Portugal, 13–16 June 2016; Volume 2, pp. 64–69.
24. Srivatsa, P.; Pandhare, A. Indoor Air Quality: IoT Solution. Available online: http://www.ijrat.org/downloads/ncpci2016/ncpci-46.pdf (accessed on 19 April 2018).
25. Salamone, F.; Belussi, L.; Danza, L.; Galanos, T.; Ghellere, M.; Meroni, I. Design and Development of a Nearable Wireless System to Control Indoor Air Quality and Indoor Lighting Quality. *Sensors* **2017**, *17*, 1021.
26. Bhattacharya, S.; Sridevi, S.; Pitchiah, R. Indoor air quality monitoring using wireless sensor network. In Proceedings of the 2012 Sixth International Conference on Sensing Technology (ICST), Kolkata, India, 18–21 December 2012; pp. 422–427.
27. Salamone, F.; Belussi, L.; Danza, L.; Ghellere, M.; Meroni, I. Design and Development of nEMoS, an All-in-One, Low-Cost, Web-Connected and 3D-Printed Device for Environmental Analysis. *Sensors* **2015**, *15*, 13012–13027.
28. Kampa, M.; Castanas, E. Human health effects of air pollution. *Environ. Pollut.* **2008**, *151*, 362–367.
29. Utell, M.J.; Frampton, M.W. Acute Health Effects of Ambient Air Pollution: The Ultrafine Particle Hypothesis. *J. Aerosol Med.* **2000**, *13*, 355–359.
30. Harrison, R.M.; Yin, J. Particulate matter in the atmosphere: Which particle properties are important for its effects on health? *Sci. Total Environ.* **2000**, *249*, 85–101.
31. Dockery, D.W.; Pope, C.A. Acute Respiratory Effects of Particulate Air Pollution. *Annu. Rev. Public Health* **1994**, *15*, 107–132.
32. Nazaroff, W.W.; Klepeis, N.E. Environmental Tobacco Smoke Particles. In *Indoor Environment*; Morawska, L., Salthammer, T., Eds.; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, Germany, 2003; pp. 245–274.
33. World Health Organization. *Air Quality Guidelines: Global Update 2005: Particulate Matter, Ozone, Nitrogen Dioxide, and Sulfur Dioxide*; World Health Organization: Copenhagen, Denmark, 2006.
34. Pope, C.A.; Dockery, D.W. Health Effects of Fine Particulate Air Pollution: Lines that Connect. *J. Air Waste Manag. Assoc.* **2006**, *56*, 709–742.
35. Pope, C.A.; Thun, M.J.; Namboodiri, M.M.; Dockery, D.W.; Evans, J.S.; Speizer, F.E.; Heath, C.W. Particulate Air Pollution as a Predictor of Mortality in a Prospective Study of U.S. Adults. *Am. J. Respir. Crit. Care Med.* **1995**, *151*, 669–674.
36. Heal, M.R.; Kumar, P.; Harrison, R.M. Particles, air quality, policy and health. *Chem. Soc. Rev.* 2012, 41, 6606.
37. Ham, S.; Lee, N.; Eom, I.; Lee, B.; Tsai, P.J.; Lee, K.; Yoon, C. Comparison of Real-time Nanoparticle Monitoring Instruments in the Workplaces. *Saf. Health Work* **2016**, *7*, 381–388.
38. Kumar, P.; Morawska, L.; Birmili, W.; Paasonen, P.; Hu, M.; Kulmala, M.; Harrison, R.M.; Norford, L.; Britter, R. Ultrafine particles in cities. *Environ. Int.* **2014**, *66*, 1–10.
39. Pope, C.A., III. Lung Cancer, Cardiopulmonary Mortality, and Long-Term Exposure to Fine Particulate Air Pollution. *JAMA* **2002**, *287*, 1132.

40. Seaton, A.; Godden, D.; MacNee, W.; Donaldson, K. Particulate air pollution and acute health effects. *Lancet* **1995**, *345*, 176–178.
41. Nel, A. ATMOSPHERE: Enhanced: Air Pollution-Related Illness: Effects of Particles. *Science* **2005**, *308*, 804–806.
42. Penttinen, P.; Timonen, K.L.; Tiittanen, P.; Mirme, A.; Ruuskanen, J.; Pekkanen, J. Ultrafine particles in urban air and respiratory health among adult asthmatics. *Eur. Respir. J.* **2001**, *17*, 428.
43. Bernstein, J.A.; Alexis, N.; Barnes, C.; Bernstein, I.L.; Nel, A.; Peden, D.; Diaz-Sanchez, D.; Tarlo, S.M.; Williams, P.B. Health effects of air pollution. *J. Allergy Clin. Immunol.* **2004**, *114*, 1116–1123.
44. Nishihara, K.; Mori, K. Relationships between epinephrine, waking time, and self-estimates for naps at night. *Physiol. Behav.* **1992**, *52*, 397–400.
45. Dockery, D.W.; Schwartz, J.; Spengler, J.D. Air pollution and daily mortality: Associations with particulates and acid aerosols. *Environ. Res.* **1992**, *59*, 362–373.
46. Anderson, J.O.; Thundiyil, J.G.; Stolbach, A. Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health. *J. Med. Toxicol.* **2012**, *8*, 166–175.
47. Clayton, C.A.; Perritt, R.L.; Pellizzari, E.D.; Thomas, K.W.; Whitmore, R.W.; Wallace, L.A.; Ozkaynak, H.; Spengler, J.D. Particle Total Exposure Assessment Methodology (PTEAM) study: Distributions of aerosol and elemental concentrations in personal, indoor, and outdoor air samples in a southern California community. *J. Expo. Anal. Environ. Epidemiol.* **1993**, *3*, 227–250.
48. Janssen, N.A.; Hoek, G.; Brunekreef, B.; Harssema, H.; Mensink, I.; Zuidhof, A. Personal sampling of particles in adults: Relation among personal, indoor, and outdoor air concentrations. *Am. J. Epidemiol.* **1998**, *147*, 537–547.
49. Ostro, B.; Chestnut, L. Assessing the Health Benefits of Reducing Particulate Matter Air Pollution in the United States. *Environ. Res.* **1998**, *76*, 94–106.
50. Chen, B.T.; Namenyi, J.; Yeh, H.C.; Mauderly, J.L.; Cuddihy, R.G. Physical Characterization of Cigarette Smoke Aerosol Generated from a Walton Smoke Machine. *Aerosol Sci. Technol.* **1990**, *12*, 364–375.
51. Spengler, J.D.; Dockery, D.W.; Turner, W.A.; Wolfson, J.M.; Ferris, B.G. Long-term measurements of respirable sulfates and particles inside and outside homes. *Atmos. Environ.* **1967**, *15*, 23–30.
52. Pope, C.A. Epidemiology of fine particulate air pollution and human health: Biologic mechanisms and who's at risk? *Environ. Health Perspect.* **2000**, *108* (Suppl. 4), 713–723.

Chapter 4

Indoor Air Quality Assessment Using a CO2 Monitoring System Based on Internet of Things

This chapter presents an IoT architecture for indoor air quality assessment by monitoring carbon dioxide. The proposed architecture is composed of a hardware prototype for ambient data collection and mobile computing technologies for data visualization and analytics. This method is based on open-source technologies with several advantages such as its modularity, scalability, low-cost, and easy installation.

The following article presents the Chapter 4.

Indoor Air Quality Assessment Using a CO2 Monitoring System Based on Internet of Things

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MOBILE & WIRELESS HEALTH

Indoor Air Quality Assessment Using a CO_2 Monitoring System Based on Internet of Things

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Abstract

Indoor air quality (IAQ) parameters are not only directly related to occupational health but also have a significant impact on quality of life as people typically spend more than 90% of their time in indoor environments. Although IAQ is not usually monitored, it must be perceived as a relevant issue to follow up for the inhabitants' well-being and comfort for enhanced living environments and occupational health. Carbon dioxide (CO_2) has a substantial influence on public health and can be used as an essential index of IAQ. CO_2 levels over 1000 ppm, indicates an indoor air potential problem. Monitoring CO_2 concentration in real-time is essential to detect IAQ issues to quickly intervene in the building. The continuous technological advances in several areas such as Ambient Assisted Living and the Internet of Things (IoT) make it possible to build smart objects with significant capabilities for sensing and connecting. This paper presents the *iAirCO₂* system, a solution for CO_2 real-time monitoring based on IoT architecture. The *iAirCO₂* is composed of a hardware prototype for ambient data collection and a Web and smartphone software for data consulting. In future, it is planned that these data can be accessed by doctors in order to support medical diagnostics. Compared to other solutions, the *iAirCO₂* is based on open-source technologies, providing a total Wi-Fi system, with several advantages such as its modularity, scalability, low-cost, and easy installation. The results reveal that the system can generate a viable IAQ appraisal, allowing to anticipate technical interventions that contribute to a healthier living environment.

Keywords AAL (ambient assisted living) · Enhanced living environments · Health informatics · IAQ (indoor air quality) · IoT (internet of things) · Smart cities

Introduction

Ambient Assisted Living (AAL) is an emerging multidisciplinary field aiming at providing an ecosystem of different types of sensors, computers, mobile devices, wireless networks and software applications for personal healthcare monitoring and telehealth systems [1]. Currently, different AAL solutions are having as basis several sensors for measuring weight, blood pressure, glucose, oxygen, temperature, location and position, and they generally use wireless technologies such as ZigBee, Bluetooth, Ethernet and Wi-Fi.

There is a lot of challenges in designing and implementation of an effective AAL system such as information architecture, interaction design, human-computer interaction, ergonomics, usability and accessibility [2]. There are also social and ethical problems such as the acceptance by the older adults and the privacy and confidentiality that should be a requirement of all AAL devices. In fact, it is also essential to ensure that technology does not replace the human care and should be used as an essential complement.

In the USA, indoor and outdoor air quality is regulated by Environmental Protection Agency (EPA). EPA found that indoor levels of pollutants may be up to 100 times higher than outdoor pollutant level and ranked poor air quality as one of the top 5 environmental risks to the public health [3].

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The problem of poor indoor air quality (IAQ) is of utmost importance affecting especially severe form the poorest people in the world who are most vulnerable presenting itself as a critical problem for world health such as tobacco use or the issue of sexually transmitted diseases [4].

High-quality research should continue to focus on the quality problems of indoor air to adopt legislation, inspection and creating mechanisms that act in real time to improve public health, both in public places such as schools and hospitals and private homes and further increase the rigorousness of the buildings construction rules. For this purpose, it is necessary to use mechanisms for monitoring in real-time to make possible the correct analysis of the quality of indoor air to ensure a healthy environment in at least spaces of public use. In most cases, simple interventions provided by home-owners and building operators can produce substantial positive impacts on IAQ such as the avoidance of smoking indoors and the use of natural ventilation are essential behaviours that should be taught to children through educational programs that address the IAQ [5].

Increase the IAQ is critical as people typically spend more than 90% of their time in indoor environments. Associations of higher indoor carbon dioxide (CO_2) concentrations with impaired work performance, increased health issues symptoms and poorer perceived air quality are well documented, and there is also an evident correlation between high levels of indoor CO_2 and high concentrations of other indoor air pollutants that are influenced by rates of outdoor-air ventilation [6]. On the one hand, when CO_2 level reaches 7–10%, a person will lose consciousness within a few minutes and may be at risk of death. On the other hand, a low concentration of CO_2 is harmless to humans; it can still cause dizziness and sleepiness leading to poor work performance [7]. These are reasons enough to monitor CO_2 and to provide notifications in real-time to improve occupational health and provide a safe and healthy indoor living environment. The concentrations of CO_2, the main greenhouse gas, are steadily increasing to 400 ppm, reaching new records every year since they began to be produced in 1984 [8].

The concept of the "smart city" has recently been introduced as a strategic device to encompass modern urban production factors in a common framework and, in particular, to highlight the importance of Information and Communication Technologies (ICTs) in the last 20 years for enhancing the competitive profile of a city as proposed by [9]. Nowadays, cities face interesting challenges and problems to meet socio-economic development and quality of life objectives and the concept of "smart cities" correspond to answer to these challenges [10]. The smart city is directly related to an emerging strategy to mitigate the problems generated by the urban population growth and rapid urbanisation [11]. The most relevant issue in smart cities is the non interoperability of heterogeneous Technologies. The Internet of Things (IoT) can provide interoperability to build a unified urban-scale ICT platform for smart cities [12]. The smart city implementation will cause impacts at distinct levels on science, technology, competitiveness and society, but also will cause ethical issues. The smart city needs to provide access to accurate information, as it becomes crucial when such information is available at a fine spatial scale where individuals can be identified [13]. IoT has a relevant potential for creating new real-life applications and services for the smart city context [14].

This paper presents a solution for CO_2 real-time monitoring based on IoT architecture. To create a low-cost system, only one type of indoor air pollutant was chosen. CO_2 was selected since it is easy to measure and it is produced in quantity (by people and combustion equipment). Thus, it can be used as an indicator of other pollutants, and therefore of the IAQ in general. The solution is composed by a hardware prototype for ambient data collection and a Web and smartphone software for data consulting. The *iAirCO₂* is based on open-source technologies and is a totality Wi-Fi system, with several advantages compared to existing systems, such as its modularity, scalability, low-cost and easy installation. The data is uploaded to a SQL SERVER database using. NET Web Services and can be accessed using a smartphone application or the Web portal. This system is based on an ESP8266 microcontroller with built-in Wi-Fi communication technology as communication and processing unit and incorporates a CO_2 sensor as sensing unit.

The paper is structured as follows: besides de introduction (Section 1), Section 2 presents the related work and Section 3 is concerned to the methods and materials used in the implementation of the sensor system; Section 4 demonstrates the system operation and experimental results, and the conclusion is presented in Section 5.

Related work

Various IAQ monitoring solutions are available in the literature and this section presents some of the related work.

A battery-free sensor that is capable to monitor IAQ in real-time that consists of three main components: an entirely passive ultra-high frequency (UHF) smart tag for communication with a UHF radio frequency identification (RFID) reader, a smart sensing module with ultra-low power sensors and a microcontroller unit (MCU), and an RF energy harvester is proposed by [15].

Several IoT architectures for IAQ monitoring that incorporate open-source technologies for processing and data transmission and microsensors for data acquisition, but also allows access to data collected from different sites simultaneously through Web access and/or through mobile applications in real-time, are proposed by [16–22].

Ozone, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, CO_2, VOC, temperature and humidity monitoring system is proposed by [16]. It incorporates a smoothing algorithm to prevent from temporary sensor errors, and an aggregation algorithm to reduce the network traffic and power consumption. The prototype sensor module is based on the Raspberry Pi. It is not a low-cost solution for IAQ regarding the components costs.

A Wireless Sensor Network (WSN) for IAQ supervision developed using Arduino, XBee modules and microsensors (temperature, humidity, carbon monoxide, CO_2 and luminosity), for storage and availability of monitoring data in real-time using an Android Application and a Web portal is proposed by [17, 18]. The solution is composed by one gateway and several sensors nodes. The gateway receives the data from the sensor nodes using ZigBee protocol, and it uses Ethernet and Web Services for data communication for enhanced occupational health. Its purpose is reducing the burden of symptoms and diseases related to sick buildings. However, this solution has a complex installation architecture regarding the nodes and coordinators configuration.

A complete wireless solution for IAQ monitoring based on IoT architecture composed by a hardware prototype for ambient data collection and a Web and smartphone software for data consulting is proposed by [19]. This solution is based on open-source technologies, and the data collected by the system is stored in a cloud IoT analytics platform named Thingspeak. Although, this solution does not provide an integrated management system for building supervision, as the Web portal is based on the ThingSpeak analytics service. The *iAirCO*$_2$ provides an integrated Web portal for building supervision which leads to a more quick intervention on the building to increase the IAQ in real-time.

A simplified ZigBee WSN system for IAQ monitoring applications based on the Arduino platform which incorporates low-cost CO_2, VOC, and temperature and humidity sensors is presented by [20]. However, similar to the previous solution [19], this system based on the Arduino platform doesn't provide any mobile computing solution for IAQ evaluation neither analytics.

An IAQ supervision system for AAL is proposed by [21]. This solution proposes a hybrid IoT/WSN architecture approach for real-time monitoring of temperature, humidity, carbon monoxide, CO_2 and luminosity. The solution is based on open-source technologies such as Arduino platform and ZigBee. The proposed gateway is wirelessly connected to the Internet using the ESP8266 module for data communication. However, it is an expensive and time-consuming solution to install and configure, and it costs a significant amount of money than *iAirCO2*. The *iAirCO2* provides several advantages in scalability and in-home installation because it is only necessary to configure the Wi-Fi connection and it is not necessary to configure the sensor nodes and coordinators.

The iDust is a real-time particulate matter exposure monitoring system and decision-making tool for enhanced healthcare based on an IoT architecture. It was developed using open-source technologies and low-cost sensors. It provides a Web portal for data consulting and alerts that can be used by the building manager to plan interventions for enhanced IAQ [22]. Despite the advantages presented in the iDust, this system does not monitor CO_2 levels, which is assumed as the most significant parameter to be collected for IAQ assessment.

IAQ monitoring is a significant requirement for global health. Therefore, the development of low-cost and open-source monitoring systems for IAQ supervision is a trending topic. Due to the quality and relevant contribution of several existing solutions [23–27], a summarised comparison review is presented in Table 1.The excessive levels of CO_2 inside classrooms is a problem known and studied for several years [25, 28–31]. Through the use of real-time monitoring and availability of data, occupational health risk situations can be

Table 1 Summary of similar researchs on IoT platform for real-time IAQ monitoring

	MCU	Sensors	Architecture	Low-Cost	Open-Source	Connectivity	Data Access	Easy Installation
Wang, S. K et al.[27]	Arduino	Temperature, Relative Humidity, CO_2	WSN	√	√	ZigBee	Desktop	×
P. Srivatsa and A. Pandhare [23]	Raspberry Pi	CO_2	WSN/IoT	√	√	Wi-Fi	Web	×
F. Salamone et al. [24]	Arduino UNO	CO_2	WSN	√	√	ZigBee	×	×
S. Bhattacharya et al. [25]	Waspmote	CO, CO_2, PM, Temperature, Relative Humidity	WSN	×	√	ZigBee	Desktop	×
F. Salamone et al. [26]	Arduino UNO	Temperature, Relative Humidity, CO_2, Ligth, Air velocity	IoT	√	√	ZigBee / BLE	Mobile	×

MCU: microcontroller; √: apply; ×: not apply.

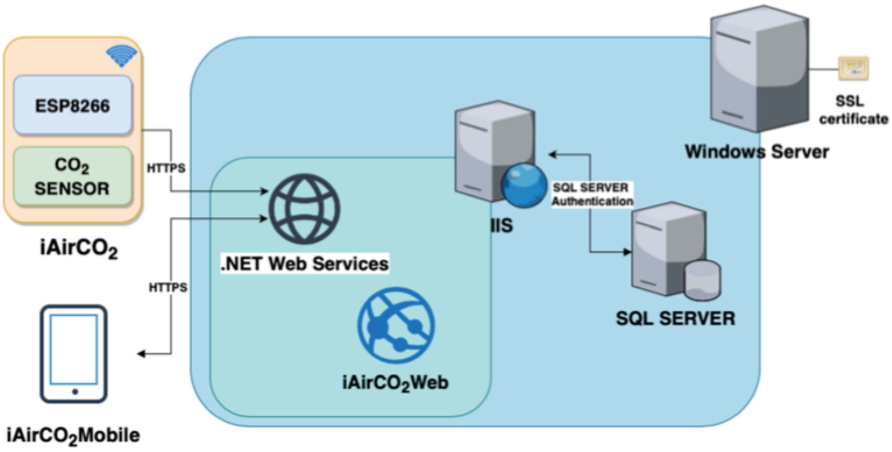


Fig. 1 *$AirCO_2$* system architecture: connection diagram and security methods used

detected and assertively intervened. The *$iAirCO_2$* system aims to provide a useful tool for management enhanced living environments of smart cities. The benefits for health, comfort and productivity of good IAQ conditions can be improved by decreasing the pollution load while the ventilation remained unchanged [32].

Materials and methods

Considering the IAQ impact on health, the authors developed a reliable, cost-effective system that can be easily configured and installed by the average user for enhanced living environments. It was selected a low-cost but very reliable CO_2 sensor and a microcontroller with native Wi-Fi support. In this section will be discussed in detail the hardware and software that make up the system as well as its construction cost.

The authors developed an utterly wireless solution using the ESP8266 module which implements the IEEE 802.11 b/g/n networking protocol. This microcontroller with built-in Wi-Fi capabilities is used both as the processing and communication unit.

The collected data is uploaded to the SQL SERVER database using. NET Web Services. This solution provides a Web portal developed in ASP.NET denominated *$iAirCO_2Web$* and a mobile application developed in SWIFT for the iOS operating system named *$iAirCO_2Mobile$* for data consulting.

The *$iAirCO_2Web$* and the. NET Web Services are hosted at the same Windows Server instance. The. NET Web Services are used to share the data collected by *$iAirCO_2$* prototype and to support the network requests from the *$iAirCO_2Mobile$*.

The *$iAirCO_2Web$* is directly connected to the SQL Server database using SQL Server authentication. To provide security for the Web Services used and to provide access only to authenticated clients, the requests messages are encrypted and signed using HTTPS. The Web Services are authenticated using an SSL (Secure Sockets Layer) certificate. In order to guarantee security, the server uses a valid X.509 certificate. The *$iAirCO_2$* system architecture is shown in Fig. 1.

This system consists of 2 components, an ESP8266 Thing Dev (Sparkfun) microcontroller and an MHZ-19 CO_2 sensor developed by Winsensor. Figure 2 represents the prototype developed by the authors.

A brief introduction of each component is shown below:

- ESP8266 is a Wi-Fi chip with integrated antenna switches, RF balun, power amplifier, low noise receive amplifier, filters and power management modules. It supports 802.11 b/g/n protocols, Wi-Fi 2.4 GHz, WPA/WPA2. It has an integrated low power 32-bit MCU and an integrated 10-bit ADC. It has a standby power consumption of

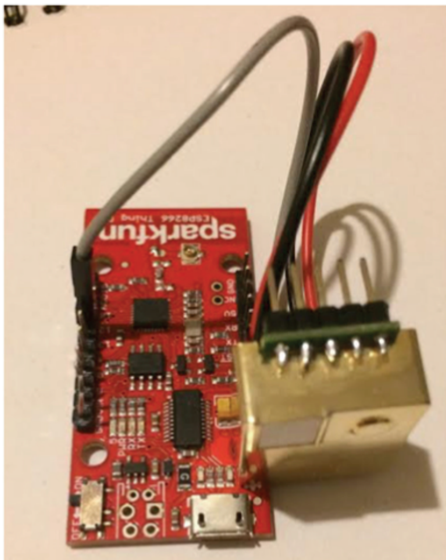


Fig. 2 *$iAirCO_2$* hardware prototype

Table 2 *iAirCO₂* system cost

Part	Cost
ESP8266	10.39USD
MHZ-19	22.90USD
Cables and Box	8.59USD
Total	41.88 USD

<1.0 mW (DTIM3) and it can operate at temperature range -40C ~ 125C [33].

- MH-Z19 NDIR (non-dispersive infrared) is a CO_2 sensor; it is non-oxygen dependent with a built-in temperature sensor for temperature compensation. It has a digital output and analogue voltage output. This sensor can operate at 0~50 °C temperature and 0~95% humidity. It has a measurement range of 0~2000 ppm, a lifespan higher than 5 years and an average current consumption lower than 10 mA. The MH-Z19 has a 3.3 V interface level and a PWM and UART output signal.

Competing systems are more expensive than *iAirCO₂* and they do not gather data in real time. This system is a suitable low-cost solution for enhanced living environments that cost around 41,88 USD. Table 2 describes the cost of the system.

The CO_2 sensor is connected to a PWM input of the ESP8266, which is the power source. The connection diagram is shown in Fig. 3. The MHZ-19 CO_2 sensor provides three connection types: analogue, PWM and I2C.

The ESP8266 Arduino Core brings support for the ESP8266 chip to the Arduino environment and supports several libraries to communicate using Wi-Fi. The Arduino Core enables the use of Arduino functions and libraries directly on ESP8266. This system is implemented using the Arduino Core with the Arduino IDE. The sensing activity is updated in every 15 s and stored in the SQL SERVER database.

The end user can configure this system. The system is by default a Wi-Fi client. If it is unable to connect to the Internet, the system will turn to hotspot mode. Then the user can connect to this Wi-Fi network and configure the credentials (Fig.4).

This functionality provides a significant advantage. As this is a turn-key solution, the system can be easily installed by the owner, that makes it more competitive and commercially interesting and attractive.

The iOS application is denominated *iAirC0₂Mobile* (Fig.5). This mobile application (app) was developed with SWIFT programming language in XCODE IDE, and it is compatible with iOS 9 and following versions [34]. This app has three essential features as it permits not only real-time consulting of the last data collected, receive real-time notifications to advise the user when the air quality is defective but also to configure the CO_2 levels for the alert. The end user can access the data from the mobile app after logged in. This app provides not only easy access to IAQ data in real time but also allows the user to keep the parameters history and providing a history of changes. The system helps the user to analyse in a precise and detailed way the air quality behaviour. The map view feature allows the user to check in real time the latest data collected by *iAirCO₂* including location.

Discussion and results

Dwelling, construction, heating, and ventilation types influence air permeability changes. It is estimated that two-thirds of commercial/services buildings with natural ventilation are extremely airtight, and the remaining third tend to be leakier.

For testing purposes, a laboratory of a Portuguese university was on-site monitored, and one *iAirCO₂* module was used. Fig. 6 represents the *iAirCO₂* installation scheme for performing the experiments carried out by the authors. The system was placed to monitoring the laboratory environment

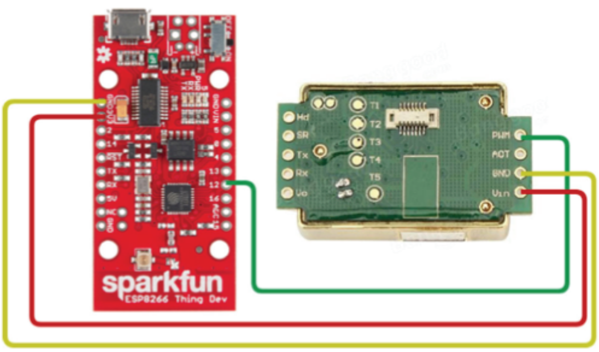


Fig. 3 *iAirCO₂* hardware connection diagram

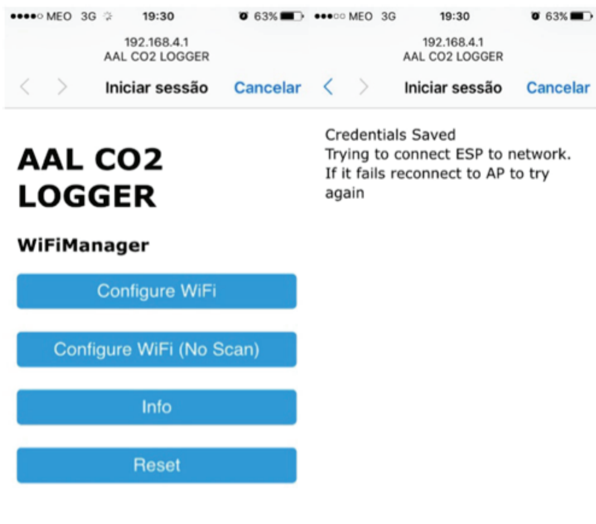


Fig. 4 *iAirCO₂* system network configuration process

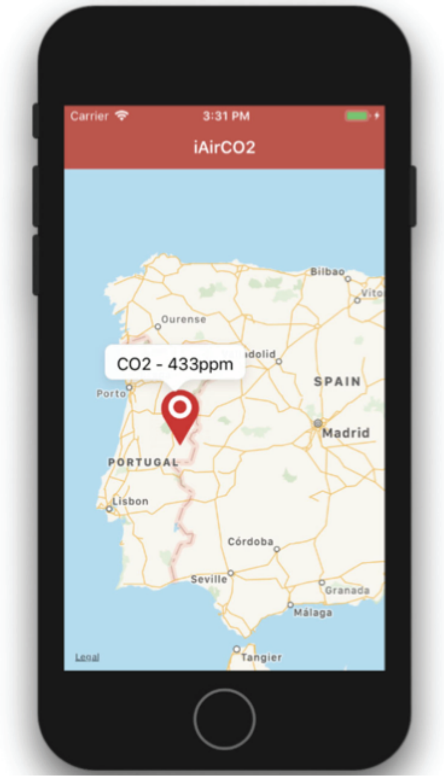


Fig. 5 *iAirCO₂Mobile* application map view

(identified with "X" in Fig. 6). The router was positioned in the corridor at a distance of about 13 m. As in most buildings, the space monitored is naturally ventilated, without any dedicated ventilation slots on the facades. Natural ventilation is performed through uncontrolled infiltration and door and windows opening.

The module is powered by a 230 V–5 V AC-DC 2A power supply. CO_2 data was collected for two months which showed that under certain conditions air quality values are significantly lower than those considered healthy for standards. The tests conducted show the system capability to analyse in real-time the IAQ, the potential to planning interventions to ensure safe healthy and comfortable conditions, but also to identify multiple situations or habits that affect the IAQ negatively.

The *iAirCO₂* data is represented in graphics and numerical formats, and are consulted using a Web browser or smartphone application. A sample of the data collected by *iAirCO₂* is shown in fig. 7; it represents the CO_2 sensor data measured in ppm.

The graphics displaying the air quality data provides a better perception of the monitored parameters behaviour than the numerical format. On the other hand, the Web and smartphone software also provides easy and quick access to collected data; this tool enables more precise analysis of parameters temporal evolution. Thus, the system is a powerful tool for analysing IAQ and to support decision making on possible interventions to improve productivity and a healthy indoor environment.

Abundant scientific evidence shows that CO_2 is the single most important climate-relevant greenhouse gas in Earth's atmosphere. High external charges naturally lead to higher indoor concentrations due to the contribution of internal sources (human metabolism and combustion equipment) [35, 36].

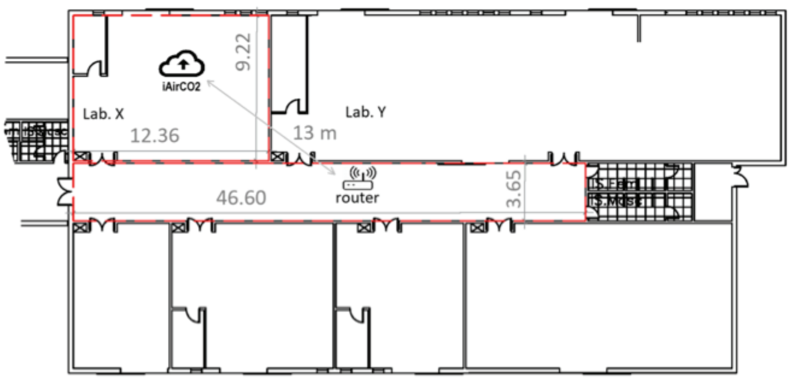
It is a need to control the concentration of CO_2 in an effective way. The first step will be to monitor it. Pollutants fluctuations records in real-time enables planning interventions for CO_2 concentration reduction.

The *iAirCO₂* is also equipped with a powerful alert manager that notifies the user when the air quality is poor. Based on values from literature, the maximum and minimum health quality values are predefined by the system, but the user can also change these values for specific purposes on the notification system (Fig.8).

When a value exceeds the defined threshold, the user will be notified in real time by e-mail, SMS or smartphone notification. The user can also check the notifications history using the Web portal (Fig. 9).

The data collected by the *iAirCO₂* system is analysed before being inserted into the database. If the data exceeds the defined thresholds, the user receives a notification. This function enables the user to act in real time ensuring indoor

Fig. 6 *iAirCO₂* installation scheme used in the experiments



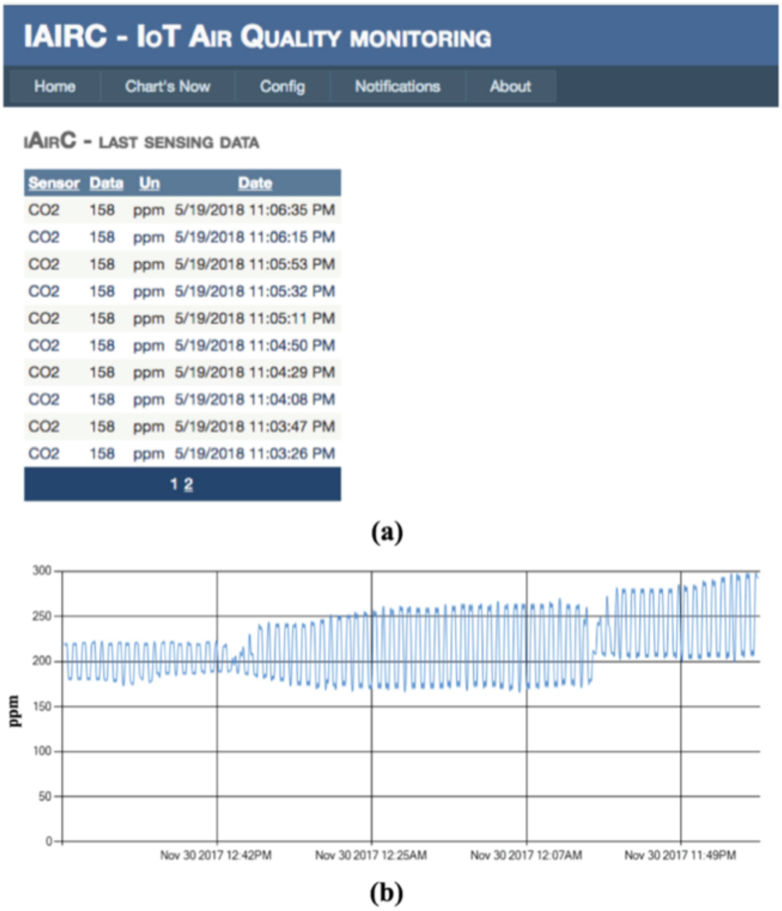


Fig. 7 Results of CO_2 concentrations monitored during the tests: (a) Web Application Table History; (b) Web Application Graphic View

ambient proper ventilation. The notification system architecture is shown in Fig. 10.

The real-time notification system provides several advantages when the purpose is achieving effective changes for enhanced living environments. In one hand, the notification messages promote behaviour changes. In fact, these messages alert the user to act in real-time providing measures to improve building IAQ. On the other hand, this real-time feature allows the building manager to recognize patters when recurrent unhealthy events are detected, and implement adjustments to prevent them to occur.

The *iAirCO₂* has advantages when compared to other systems. It is easy to install and configure due to the use of wireless technology and its small size (about 5.5 cm × 2.5 cm × 2.5 cm depth). Also, it is equipped with a smartphone and Web application to provide access to the recorded data at any time from anywhere.

The $iAirCO_2$ provides entirely solution for data analysis and notifications. It is a support tool for building interventions planning. It can be shared with medical teams to help with diagnostics. Individuals spend most of the time indoors, therefore, it is necessary to monitor the CO_2 level to change habits and even to plan ventilation interventions for a healthier living environment and productivity improvement. This system makes a significant contribution compared to existing air quality monitoring systems due to its low-cost of construction, installation, modularity, scalability and easy access to monitoring data in real time through the Web application.

The $iAirCO_2$ system uses the ESP8266 for both processing and Internet connectivity; it offers several advantages regarding system cost reduction, but also improves processing power because the ESP8266 has an 80 MHZ CPU, while the Arduino UNO used in several IAQ monitoring solutions has only a 16 MHZ CPU. The use of the ESP8266 has another important feature: it makes to the end user easyly to configure the Wi-Fi network to which $iAirCO_2$ is connected.

The $iAirCO_2$ prototype CO_2 sensor selection was carefully conducted in order to create not only a low-cost but also a reliable IAQ supervision system. Besides, an industrial level CO_2 sensors can be incorporated in the $iAirCO_2$ for enhanced accuracy.

In the future, the main goal is to make technical improvements to the prototype including the development of additional relevant notifications methods to notify the user when the

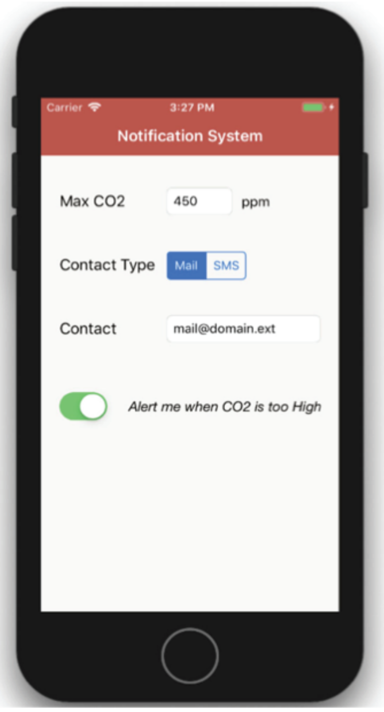


Fig. 8 Notification configuration process

quality of indoor air has serious deficiencies such as smartwatch compatibility. Improvements to the system hardware and software are planned to make it much more appropriate for specific purposes such as hospitals, schools and offices. The authors also plan to test other messaging protocols and data communication technologies, such as MQTT and LoRa respectively. It will be implemented device management protocols such as Mobile Alliance's Device Management (OMA DM) and Lightweight Machine-to-Machine (OMA LwM2M) for enhanced device management and configuration.

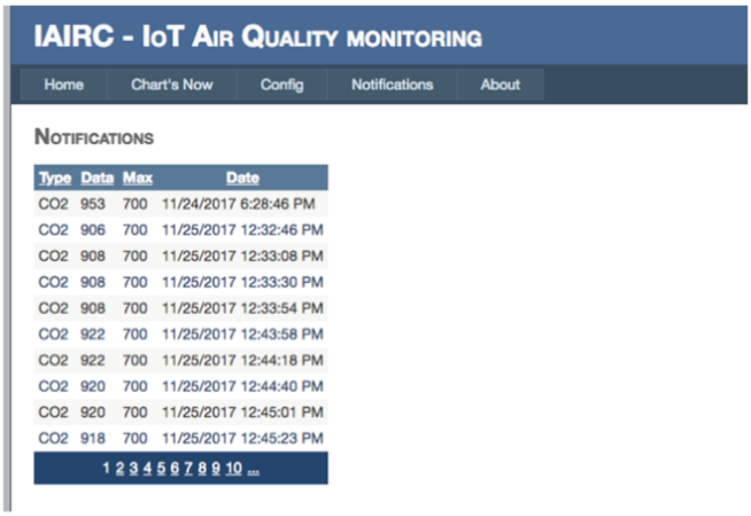
Most of IAQ monitoring solutions require professional installers. The *iAirCO₂* system can be installed by a typical user; this contributes to keep the low-cost of this IoT solution. The notification system allows users to act in real time to significantly improve IAQ through the ventilation or deactivation of pollutant equipment.

Conclusion

One of the best indicators of the IAQ conditions is the CO_2 level. It is emitted in large quantities and is relatively easy to measure. CO_2 is a useful quantitative indicator of human presence in a room. Also, it can be used as an indirect indicator of high concentrations of other pollutants. Consequently, it becomes an indicator of the degradation of the IAQ as a whole. The CO_2 level data is useful in providing support to a clinical analysis performed by health professionals. We spend about 90% of our lives in indoor environments. Only IAQ monitoring makes it is possible to perceive accurately the ventilation conditions that influence the occupant's health. It provides the data to plan interventions to decrease the CO_2 levels if needed.

This paper had described an IoT architecture for CO_2 real-time monitoring composed by a hardware prototype for ambient data collection and a Web and smartphone software for data consulting. The results obtained are auspicious, representing a significant contribution to CO_2 monitoring systems based on IoT. In the one hand, the monitored data can be particularly valuable to offer support to a medical diagnosis by clinical professionals as the medical team might analyse the history of IAQ parameters of the ecosystem everywhere the patient lives.

Fig. 9 Notification history table



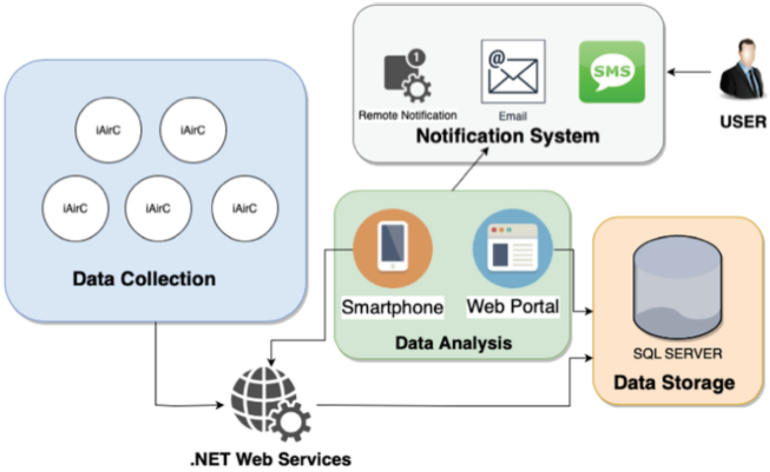


Fig. 10 *iAirCO₂* notifications architecture

It can be related to the records with health complications. On the other hand, it is possible to detect poor air conditions, and at a very early stage, intervention plans can be set up for enhanced occupational health.

When comparing to existing systems, it is advantageous due to the use of low-cost and open-source technologies but also due to its easy installation. The system has advantages both in installation and configuration, due to the use of wireless technology for communication. Also, it was developed to be compatible with all domestic house devices and not only for smart houses or high-tech houses.

In the future, it is expected to introduce new monitoring products to create an ecosystem for IAQ as well as the development of a platform that allows data sharing in a secure way to health professionals to support medical diagnostics. The authors are planning software and hardware improvements to adapt the system to specific cases such as hospitals, schools and industry. We believe that systems like this will contribute to enhanced living environments but also be an integral part of the daily human routine.

Compliance with Ethical Standards

Conflicts of Interest The authors declare no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

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References

1. Universal Open Platform and Reference Specification for Ambient Assisted Living: http://www.universaal.org/.
2. Koleva, P., Tonchev, K., Balabanov, G., Manolova, A., Poulkov, V., Challenges in designing and implementation of an effective ambient assisted living system. Telecommunication in modern satellite, cable and broadcasting services (TELSIKS), 2015 12th international conference on. 305–308, 2015.
3. Seguel, J. M., Merrill, R., Seguel, D., and Campagna, A. C., Indoor air quality. *Am. J. Lifestyle Med.* 11(4):284–2895, 2016.
4. Bruce, N., Perez-Padilla, R., and Albalak, R., Indoor air pollution in developing countries: A major environmental and public health challenge. *Bull. World Health Org.* 78(9):1078–1092, 2000.
5. Jones, A. P., Indoor air quality and health. *Atmosph. Environ.* 33(28):4535–4564, 1999.
6. Satish, U. et al., Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance. Environmental Health Perspectives, 2012.
7. Yu, T.-C. et al., Wireless sensor networks for indoor air quality monitoring. *Med. Eng. Phys.* 35(2):231–235, 2013.
8. Myers, S. S. et al., Increasing CO2 threatens human nutrition. *Nature* 510(7503):139–142, 2014.
9. Caragliu, A., Del Bo, C., and Nijkamp, P., Smart cities in Europe. *J. Urb. Technol.* 18(2):65–82, 2011.
10. Schaffers, H., Komninos, N., Pallot, M., Trousse, B., Nilsson, M., and Oliveira, A., Smart cities and the future internet: Towards co-operation frameworks for open innovation. In: Domingue, J., Galis, A., Gavras, A., Zahariadis, T., Lambert, D., Cleary, F., Daras, P., Krco, S., Müller, H., Li, M.-S., Schaffers, H., Lotz, V., Alvarez, F., Stiller, B., Karnouskos, S., Avessta, S., Nilsson, M. (Eds), The future internet. Vol. 6656. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, 431–446.
11. Chourabi, H. et al., Understanding smart cities: An integrative. *Framework*:2289–2297, 2012.
12. Zanella, A., Bui, N., Castellani, A., Vangelista, L., and Zorzi, M., Internet of things for smart cities. *IEEE Internet Things J.* 1(1):22–32, 2014.
13. Batty, M. et al., Smart cities of the future. Eur. Phys. J. Spec. Topics 214(1):481–518, 2012.
14. Hernández-Muñoz, J. M. et al., Smart cities at the forefront of the future internet. In: Domingue, J., Galis, A., Gavras, A., Zahariadis, T., Lambert, D., Cleary, F., Daras, P., Krco, S., Müller, H., Li, M.-S., Schaffers, H., Lotz, V., Alvarez, F., Stiller, B., Karnouskos, S., Avessta, S., Nilsson, M. (Eds), The future internet. Vol. 6656. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, 447–462.
15. Tran, T. V., Dang, N. T., and Chung, W.-Y., Battery-free smart-sensor system for real-time indoor air quality monitoring. Sensors and Actuators B: Chemical, 2017.

16. Kim, J.-Y., Chu, C.-H., and Shin, S.-M., ISSAQ: An integrated sensing systems for real-time indoor air quality monitoring. *IEEE Sens. J.* 14(12):4230–4244, 2014.
17. Marques, G. and Pitarma, R., Health informatics for indoor air quality monitoring. Information Systems and technologies (CISTI), 2016 11th Iberian conference on. 1–6, 2016.
18. Pitarma, R., Marques, G., and Ferreira, B. R., Monitoring indoor air quality for enhanced occupational health. *J. Med. Syst.* 41, no. 2, 2017.
19. Marques, G., and Pitarma, R., Monitoring health factors in indoor living environments using internet of things. In: Rocha, Á., Correia, A. M., Adeli, H., Reis, L. P., Costanzo, S. (Eds), Recent advances in information Systems and technologies. Vol. 570. Cham: Springer International Publishing, 2017, 785–794.
20. Abraham, S., and Li, X., A cost-effective wireless sensor network system for indoor air quality monitoring applications. *Proc. Comput. Sci.* 34:165–171, 2014.
21. Marques, G., and Pitarma, R., An indoor monitoring system for ambient assisted living based on internet of things architecture. *Int. J. Environ. Res. Publ. Health* 13(11):1152, 2016.
22. Marques, G., Roque Ferreira, C., and Pitarma, R., A system based on the internet of things for real-time particle monitoring in buildings. *Int. J. Environ. Res. Publ. Health* 15(4):821, 2018.
23. Srivatsa, P. and Pandhare, A., Indoor air quality: IoT solution. *National Conference* "*NCPCI*, 2016. 19, 2016.
24. Salamone, F., Belussi, L., Danza, L., Galanos, T., Ghellere, M., and Meroni, I., Design and development of a nearable wireless system to control indoor air quality and indoor lighting quality. *Sensors* 17(5):1021, 2017.
25. Bhattacharya, S., Sridevi, S., and Pitchiah, R., Indoor air quality monitoring using wireless sensor network. 422–427, 2012.
26. Salamone, F., Belussi, L., Danza, L., Ghellere, M., and Meroni, I., Design and development of nEMoS, an all-in-one, low-cost, web-connected and 3D-printed device for environmental analysis. *Sensors* 15(6):13012–13027, 2015.
27. Wang, S. K., Chew, S. P., Jusoh, M. T., Khairunissa, A., Leong, K. Y., and Azid, A. A., WSN based indoor air quality monitoring in classrooms. 020063, 2017.
28. Lee, S. ., and Chang, M., Indoor and outdoor air quality investigation at schools in Hong Kong. *Chemosphere* 41(1–2):109–113, 2000.
29. Seppanen, O. A., Fisk, W. J., and Mendell, M. J., Association of Ventilation Rates and CO2 concentrations with health andOther responses in commercial and institutional buildings. *Indoor Air* 9(4):226–252, 1999.
30. Ramachandran, G. et al., Indoor air quality in two urban elementary schools—Measurements of airborne Fungi, carpet allergens, CO_2, temperature, and relative humidity. *J. Occup. Environ. Hyg.* 2(11): 553–566, 2005.
31. Scheff, P. A., Paulius, V. K., Huang, S. W., and Conroy, L. M., Indoor air quality in a middle school, part I: Use of CO_2 as a tracer for effective ventilation. *Appl. Occup. Environ. Hyg.* 15(11):824–834, 2000.
32. Wargocki, P., Wyon, D. P., Sundell, J., Clausen, G., and Fanger, P. O., The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. *Indoor Air* 10(4):222–236, 2000.
33. Espressif Systems, "ESP8266EX Datasheet," http://download.arduino.org/products/UNOWIFI/0A-ESP8266-Datasheet-EN-v4.3.pdf, 2015.
34. Neuburg, M., iOS 7 programming fundamentals: Objective-c, xcode, and cocoa basics. O'Reilly Media, Inc., 2013.
35. Lacis, A. A., Schmidt, G. A., Rind, D., and Ruedy, R. A., Atmospheric CO2: Principal control knob governing Earth's temperature. *Science* 330(6002):356–359, 2010.
36. Awbi, H. B., Ventilation of buildings. Taylor & Francis, 2003.

Chapter 5

A Cost-Effective Air Quality Supervision Solution for Enhanced Living Environments through the Internet of Things

This chapter presents an IoT architecture for real-time air quality monitoring composed by an ESP8266 and a MICS-6814. The proposed method incorporates several gases sensorial capabilities such as carbon monoxide, nitrogen dioxide, ethanol, methane, and propane. This architecture incorporates a mobile and Web Framework for data consulting and notifications and Cloud service for data storage.

The following article presents the Chapter 5.

A Cost-Effective Air Quality Supervision Solution for Enhanced Living Environments through the Internet of Things

Gonçalo Marques and Rui Pitarma

Electronics (MDPI), published, 2019.

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Impact Factor: 2.110

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Article

A Cost-Effective Air Quality Supervision Solution for Enhanced Living Environments through the Internet of Things

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Abstract: We spend about 90% of our lives in indoor living environments. Thus, it is essential to provide indoor air quality monitoring for enhanced living environments. Advances in networking, sensors, and embedded devices have made monitoring and supply of assistance possible to people in their homes. Technological advancements have made possible the building of smart devices with significant capabilities for sensing and connecting, but also provide several improvements in ambient assisted living system architectures. Indoor air quality assumes an important role in building productive and healthy indoor environments. In this paper, the authors present an Internet of Things system for real-time indoor air quality monitoring named *iAir*. This system is composed by an ESP8266 as the communication and processing unit and a MICS-6814 sensor as the sensing unit. The MICS-6814 is a metal oxide semiconductor sensor capable of detecting several gases such as carbon monoxide, nitrogen dioxide, ethanol, methane, and propane. The *iAir* system also provides a smartphone application for data consulting and real-time notifications. Compared to other solutions, the *iAir* system is based on open-source technologies and operates as a totally Wi-Fi system, with several advantages such as its modularity, scalability, low cost, and easy installation. The results obtained are very promising, representing a meaningful contribution for enhanced living environments as *iAir* provides real-time monitoring for enhanced ambient assisted living and occupational health.

Keywords: ambient assisted living (AAL); enhanced living environments; health monitoring; indoor air quality (IAQ); IoT (Internet of Things); occupational health; smart cities

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1. Introduction

In 2050, 20% of the total population will be aged 60 years or older [1]; consequently, the expansion of disorders, medical services costs, and lack of caregivers will lead to significant social impact. Therefore, ambient assisted living (AAL) is a relevant field of research. The AAL innovations are intended to address the challenge of ageing populations to keep their independence as long as possible. Actually, 87% of individuals prefer to remain in their homes and bear the significant cost of nursing care [2].

On one hand, continuous technological advances have made possible the building of smart devices with significant capabilities for sensing and connecting to provide several advancements in AAL system architectures [3–5]. In particular, the advances in networking, sensors, and embedded systems enable real-time monitoring for enhanced living environments and healthcare [6]. On the other hand, there is a vast array of challenges in the design and implementation of an effective AAL system, such as information architecture, interaction design, human–computer interaction, ergonomics, usefulness, and accessibility [7]. There are also social and ethical issues, such as the acceptance by the older adults and the privacy and confidentiality that should be a requisite of AAL solutions. It is imperative to ensure that technology does not replace human care and should be used as an essential complement.

Internet of Things (IoT) is a paradigm where objects are connected to the internet and support sense capabilities. The pervasive presence of a variety of things or objects that can be accessed through unique addressing schemes with interaction and cooperation features is the base of the IoT concept [8]. IoT has significant influence on smart manufacturing, providing optimization and automation to administration processes such as entry and exit registration. On one hand, the IoT can be used to provide product trackability in the manufacturing process, allowing it to be managed remotely, leading to cost reductions. On the other hand, the IoT presents an important role in process automation and predictive analytics, delivered by the incorporation of artificial intelligence algorithms for enhanced performance [9].

Tendentiously, IoT devices should be ubiquitous, context-aware, and enable ambient intelligence features closely related to AAL [10]. IoT hardware is related to radio-frequency identification (RFID), near field communication (NFC), and sensor networks at the hardware level, working with standards and protocols to support machine-to-machine communication such as those envisioned for the semantic web.

IoT holds the promise of improving people's lives through both automation and augmentation at low cost [11]. However, several challenges are related to the IoT and AAL, such as security, privacy, and legal questions [12–14]. As IoT devices are typically wireless and exposed to a public range, the ownership of data collected from IoT devices must be established [15]. A significant mobile edge computing framework to provide continuous computing services for the IoT using unmanned aerial vehicles (UAV) was proposed by the authors of [16].

Indoor air quality (IAQ) assumes an important role as far as personal exposure to pollutants is concerned because several groups of people, such as the retired, students in classrooms, and disabled persons, could stay most of their time in indoor environments. Thus, IAQ supervision is a significant method for enhanced living environments and occupational health [17].

The legislation and inspection mechanisms should be adapted to act in real-time to improve global health in living environments by developing enhanced regulations for the construction and monitoring of buildings.

Simple interventions provided by homeowners and real-time monitoring produce substantial positive impacts on the IAQ [18]. Therefore, it is essential to monitor the IAQ in real-time to detect unhealthy situations and plan interventions in the building for enhanced occupation health.

However, IAQ assurance using electrical devices is highly energy-expensive. Therefore, a smart IoT platform to analyze electricity consumption of air conditioners with a deep belief network algorithm was presented by the authors of [19]. Using IAQ supervision and smart meters for energy analysis, the air conditioner usage practices can be optimized to improve energy efficiency.

This paper presents the *iAir* system, an IAQ monitoring solution based on the IoT composed of a hardware prototype for environment sensing and web/smartphone interface for data access. This system uses an open-source ESP8266 as the processing and communication unit and a MICS-6814 air sensor as a sensing unit. The data collected is uploaded to ThingSpeak, an open-source IoT application which provides an application programming interface (API) to store and retrieve data in the cloud. On the one hand, this data can be accessed by the building supervisor to detect unhealthy conditions in real-time and plan interventions to provide a more productive and healthier living environment for the occupants and be used as a decision-making tool. On the other hand, this data can be accessed by doctors to support diagnoses and to correlate patients' symptoms and health problems with the environment where they live.

Until now, several projects that aim at the creation of IAQ real-time monitoring solutions have been reported in the literature. Several IoT architectures for IAQ monitoring that incorporate open-source technologies for processing and data transmission and microsensors for data acquisition, but also allow access to data collected from different places simultaneously using mobile computing have been proposed by various groups [20–29]. In particular, an IAQ system based on an IoT paradigm that incorporates in its construction an Arduino, ESP8266, and XBee technologies for processing and data transmission and microsensors for data acquisition to be accessed by doctors, aiming to support medical diagnostics, is proposed by the authors of [30].

The rest of this paper is structured as follows: Section 2 presents health effects of the monitored pollutants, and Section 3 is concerned with the methods and materials used in the implementation of the sensor system; Section 4 demonstrates the system operation and experimental results, and the conclusion is presented in Section 5.

2. IAQ Monitored Pollution Sources and their Effects on Health

The *iAir* system is capable of collecting sensor data about several air quality parameters, such as NH_3 (ammonia), CO (carbon monoxide), NO_2 (nitrogen dioxide), C_3H_8 (propane), C_4H_{10} (butane), CH_4 (methane), H_2 (hydrogen), and C_2H_5OH (ethanol). Controlling the concentrations of these gases is extremely important to provide healthy living environments. In this section, the negative effects of the monitored pollutants are described to justify the necessity to supervise these parameters.

Ammonia has different sources, such as the inhabitants and their activities, tobacco smoke, detergents containing ammonia, paints, interior drainage pipes, indoor decoration materials, and concrete admixtures [31,32]. It is a major gaseous compound with a highly hydrophilic base in the air of livestock buildings, and it is capable of reducing daily weight gain and feed utilization [33]. In northern Europe, there has been concern about indoor ammonia and possible health effects, as ammonia exposure problems are referred to in the literature [34–36]. Ammonia is also considered as the main variable for determining air quality and a significant contributor to health and equipment deterioration [37–39].

CO is an odorless, tasteless, and nonirritating gas formed by hydrocarbon combustion. The atmospheric concentration of CO is typically below 0.001%, but it may be much higher in indoor environments [40]. CO poisoning is usual, potentially fatal, and probably underdiagnosed because of its nonspecific clinical presentation [41]. In Britain, between 40 and 50 deaths from CO poisoning are reported per year by the National Health Service [42], and in the US (United States), the same results in more than 50,000 emergency department visits per year [43]. Therefore, it is important to install automatic systems for real-time detection of CO poisoning for enhanced occupational health [44].

NO_2 is a result of combustion that has become documented as a significant component of IAQ [45]. On one hand, short-term NO_2 exposure in indoor environments followed several hours later by allergen inhalation enhances allergen-induced late asthmatic reaction [46,47]. On the other hand, NO_2 exposure causes increased airway responsiveness in healthy and asthmatic subjects, but exercise during exposure may modify this response in asthmatics [48]. Exposure to indoor NO_2 is also associated with respiratory symptoms among children with asthma in multifamily housing [49–51]. There is consistent evidence of a relationship between NO_2, as a proxy for traffic-sourced air pollution exposure, with lung cancer [52]. So, it is essential to provide NO_2 real-time monitoring, especially for children and asthmatic patients.

Liquid petroleum gas (LPG), also referred to as propane or butane, is a flammable mixture of hydrocarbon gases used as fuel in heating appliances, cooking equipment, and vehicles. LPG is clean, burns efficiently, is easy to use, reduces cooking time, and can significantly reduce emissions [53]. The use of LPG gas stoves negatively affects indoor volatile organic compound (VOC) levels in domestic kitchens [54]. Use of LPG cookstoves during cooking may cause the accumulation of high concentrations of pollutants, particularly in the indoor environment [55].

LPG has become more widely available with a supply infrastructure to meet demand in many countries [56]. Using IAQ real-time monitoring, these situations could be avoided and early interventions could be made in the building to provide enhanced occupational health.

Methane differs from other VOCs in that it is mainly of biological origin. It is colorless, odorless, and nontoxic, although in very high concentrations, it can cause asphyxia by starving the air of oxygen. Methane is a short-lived greenhouse gas and ozone precursor that affects background ozone concentrations. Controlling methane emissions may be a promising means of simultaneously mitigating climate change and reducing global ozone concentrations [57]. The *iAir* system provides real-time monitoring of CH_4 concentrations. Therefore, when the concentration exceeds healthy levels, a notification is sent to the building manager to prevent explosions with catastrophic results.

VOCs refers to organics chemicals that are present mostly as gases at room temperature. Most VOCs are at low concentrations indoors, but depending on occupant behavior, the concentrations can be are highly variable. For example, in some homes, ethanol concentrations are above 1000 $\mu g/m^3$ [58]. Ethanol is present in a large variety of products used for personal care and home maintenance, such as antiseptic wipes, hand sanitizers, body lotions, perfumes, shaving products, hair care products, some pharmaceuticals, soaps, detergents, dishwashing liquids, reed diffusers, air fresheners, and floor cleaners. Proper usage and storage of these products are highly recommended to minimize exposure to ethanol and other VOCs in general. For these reasons, it is extremely important to provide real-time monitoring to identify significant problems in IAQ.

3. Materials and Methods

Poor IAQ represents a key factor and threat for public health problems as many people spend more than 90% of their time indoors. Several pollutants such as tobacco smoke, radon decay products, carbon monoxide, nitrogen dioxide, formaldehyde, asbestos fibers, microorganisms, and aeroallergens are intimately related to health problems [59]. Temperature and humidity monitoring are part of daily life, but in the overwhelming majority of buildings, real-time air quality monitoring is not performed. With the goal of creating a real-time, low-cost, and easy-to-install air quality monitoring solution, the *iAir* system was developed by the authors.

The *iAir* system is an IAQ monitoring solution that is capable of measuring these pollutants in real-time as well as providing real-time alerts of the excessive concentration of these gases.

This system is an entirely wireless solution developed using the ESP8266 module, which implements the IEEE 802.11 b/g/n networking protocol, a family of specifications developed by the IEEE for WLANs. The IEEE 802.11 standard supports radio transmission within the 2.4 GHz band.The data collected from the indoor living environment are stored in a ThingSpeak platform. This IoT application enables one to aggregate, visualize and analyze live data streams in the cloud. For data consulting, this solution uses a web page provided by the ThingSpeak platform and a mobile phone application developed in Swift for the iOS operating system (Figure 1).

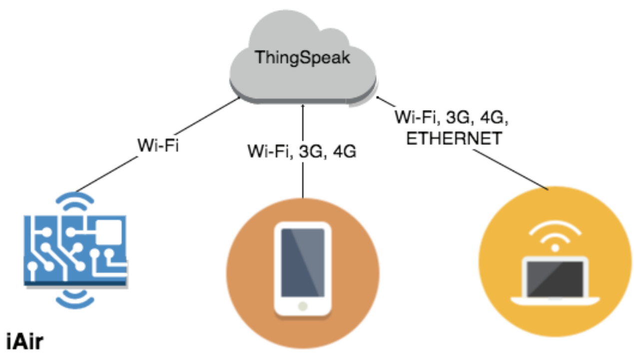


Figure 1. *iAir* system architecture.

Providing a history of pollutant concentration in real-time helps in the building manager analysis concerning the precise and detailed information about the health of the living environment, as well as in planning interventions to improve IAQ.

The *iAir* can be divided into two parts: a processing and communication unit and a sensing unit. This system is built using the ESP8266 as a microcontroller and using the built-in Wi-Fi communication feature for internet connection. The sensing unit incorporates a MICS-6814 sensor that is capable of measuring several pollutants.

Table 1 represents the air quality gases monitored by the *iAir* solution and the resolution range. The typical accuracy for the MICS-6814 is ±15–25% [60]. The sensor sensitivity varies according to the gas measured: 0.05 ppm (NO_2), 1 ppm (CO, H_2, and NH_3), 10 ppm (C_2H_6OH), and 1000 ppm (CH_4, C_3H_8, and C_4H_{10}). This sensor was selected based on its ability to monitor various gases and having low cost. It is, however, usually recognized that the lower the price, the lower the accuracy. Nevertheless, in most applications, a qualitative assessment is sufficient to provide healthy environments and promote occupational health. So, it is perfectly suited to inspect the qualitative historical evolution of the contaminants to detect unhealthy cases.

Table 1. Gases monitored by the *iAir* system.

Air Pollutant	Range
Carbon monoxide (CO)	1–1000 ppm
Nitrogen dioxide (NO_2)	0.05–10 ppm
Ethanol (C_2H_6OH)	10–500 ppm
Hydrogen (H_2)	1–1000 ppm
Ammonia (NH_3)	1–500 ppm
Methane (CH_4)	>1000 ppm
Propane (C_3H_8)	>1000 ppm
Isobutane (C_4H_{10})	>1000 ppm

Figure 2 represents the *iAir* case prototype developed in the Sketchup software and printed using a 3D printer. A brief description of the used components is presented below.

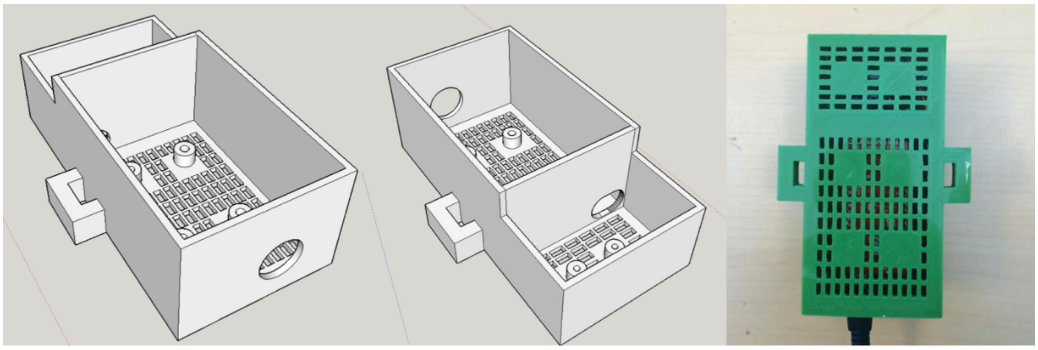


Figure 2. *iAir* prototype.

ESP8266 is a Wi-Fi chip with integrated antenna switches, RF balun, power amplifier, low noise amplifier, filters, and power management modules. It supports 802.11 b/g/n protocols, 2.4 GHz Wi-Fi, and WPA/WPA2, has an integrated low-power 32-bit MCU, an integrated 10-bit ADC, has a standby power consumption of <1.0 mW (DTIM3), and can operate in the temperature range of approx. −40 °C–125 °C [61].

MICS-6814 is a compact metal oxide semiconductor (MOS) sensor with three fully independent sensing elements in one package. It is a robust and energy efficiency sensor. The *iAir* incorporates an I2C Groove Multichannel Gas Sensor that supports three fully independent sensing elements in one package. It is built with an ATmega168PA and provides a I2C interface with a programmable address. It also allows disabling the heating functionality for low power.

The firmware of the *iAir* is implemented using the Arduino Core that is an open-source platform that aims to enable the use of common Arduino functions and libraries directly on the ESP8266 MCU (microcontroller unit) without an external microcontroller.

The data collected is transferred to a ThingSpeak channel using HTTP, API secret key, and channel ID. ThingSpeak stores the data in a channel; each channel has up to 8 data fields, a location field, and a status field. The *iAir* sends the collected data every 30 seconds (Figure 3).

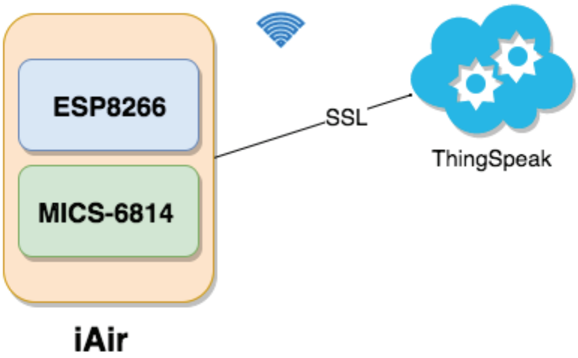


Figure 3. *iAir* and ThingSpeak platform communication.

The *iAir* is a suitable cost-effective solution for enhanced living environments, which costs an estimated 59.88 USD (Table 2).

Table 2. Cost of the *iAir* system.

Component	Cost
ESP8266	10.39 USD
MICS-6814	39.90 USD
Cables and box	9.59 USD
Total	59.88 USD

At present, IAQ monitoring solutions for residential and/or commercial/service buildings are expensive and are based on random sampling. However, these procedures are limiting by providing only information related to a specific sampling and being devoid of spatiotemporal behavior. Some of these solutions offer portability and are compact, offering data logging on the equipment itself, but do not allow real-time data availability for building managers to enable rapid and efficient intervention to improve occupational health. The solutions available on the market are expensive and do not offer mobile compatibility for data consulting and notifications. Table 3 presents a summary of the solutions available in the market; prices were obtained from Amazon (accessed on 23/01/2019).

Table 3. Monitoring solutions available on the market.

	Air Pollutant	Range	Price
SMART SENSOR AR8500	NH_3	0–100 ppm	280 USD
FORENSICS NR3000	NH_3	0–1000 ppm	240 USD
QIRUY NH3 MONITOR	NH_3	0–100 ppm	170 USD
BW GAXT-A-DL	NH_3	0–100 ppm	490 USD
SENSOR INSPECTOR PRO	CO	0–2000 ppm	200 USD
KLEIN TOOLS ET100	CO	0–1000 ppm	100 USD
SMART SENSOR AR8900	NO_2	0–20 ppm	300 USD

Most of the solutions on the market only allow a history of data limited to the device memory and require data downloading and manipulation procedures with specific software. In this way, the development of innovative environmental monitoring systems based on state-of-the-art technologies that allow real-time analysis becomes essential. Thus, the *iAir* project aims to develop a monitoring system with integrated technology, combining sensitivity, flexibility, and accuracy of measurement in real-time, allowing significant evolution of the current air quality controls. The *iAir* system provides easy, intuitive, and fast access to building air quality data as well as essential notifications in the case of poor ambient quality to provide real-time intervention and improve occupational health.

For test validation and research, an iOS application was developed with the Swift programming language in Xcode IDE (integrated development environment) and is compatible with iOS 7 and above [62]. Therefore, the minimum requirements to install the mobile application is an iPhone 4 or above with 512 MB of RAM and an Apple A4 CPU. This app, named *iAirMobile,* has two important features, as it permits not only real-time consulting of the last data collected, but access to the history of the air quality parameters in the graphical representation and also receiving real-time notifications to advise the user of when the air quality is defective. However, the Android and Windows users can still use the web portal for data consulting. Regarding the considerable Android market quota, the authors plan to develop an Android version of the mobile application to support the notification features for those users.

4. Results and Discussion

The *iAir* system allows data consulting in terms of graphical or numerical values using the web or a smartphone interface. Samples of the data collected by the system are shown in Figures 4–6 for different air pollutants.

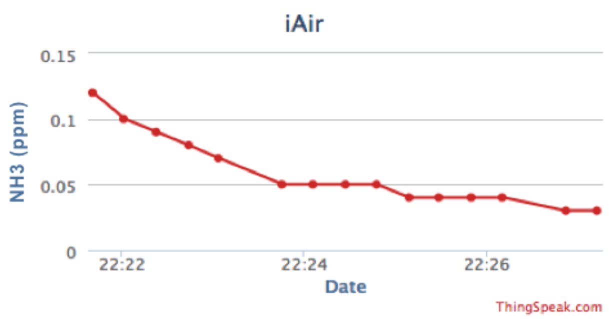


Figure 4. NH_3 concentration (ppm); data obtained in the tests performed.

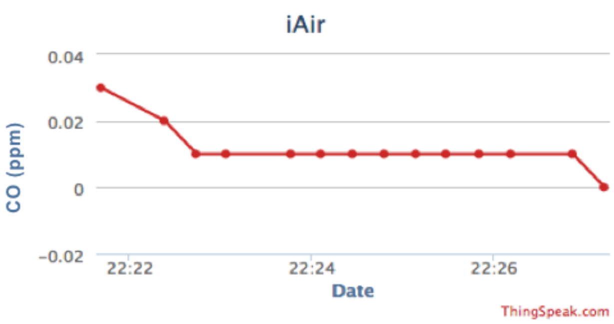


Figure 5. CO concentration (ppm); data obtained in the tests performed.

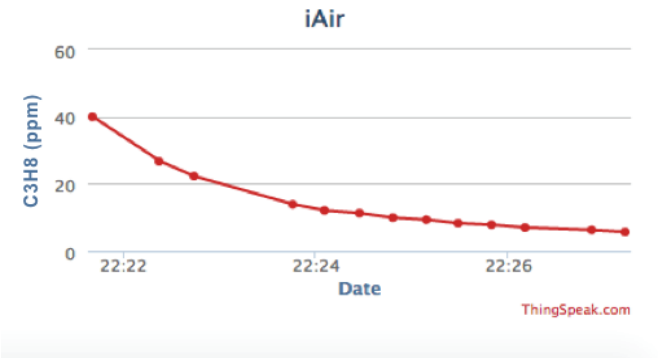


Figure 6. C_3H_8 concentration (ppm); data obtained in the tests performed.

Figure 7 represents the experiment architecture of the *iAir* solution. For testing purposes, a laboratory of the Higher Education Institution in Portugal was monitored. The *iAir* was powered using a 5 V 10,000 mA power bank connected by a micro USB cable. The data collected shows that under defective ventilation, IAQ levels are very different from the typical values for living environments.

The IAQ supervision and analysis in real-time not only can be assumed as a relevant decision-making tool to plan behaviour changes for enhanced occupational health, but also to recognise unhealthy conditions. Figure 7 represents the installation scheme.

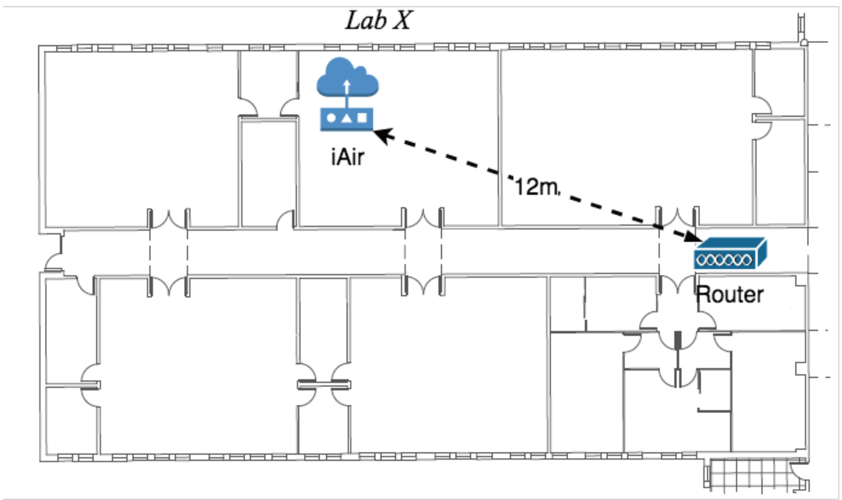
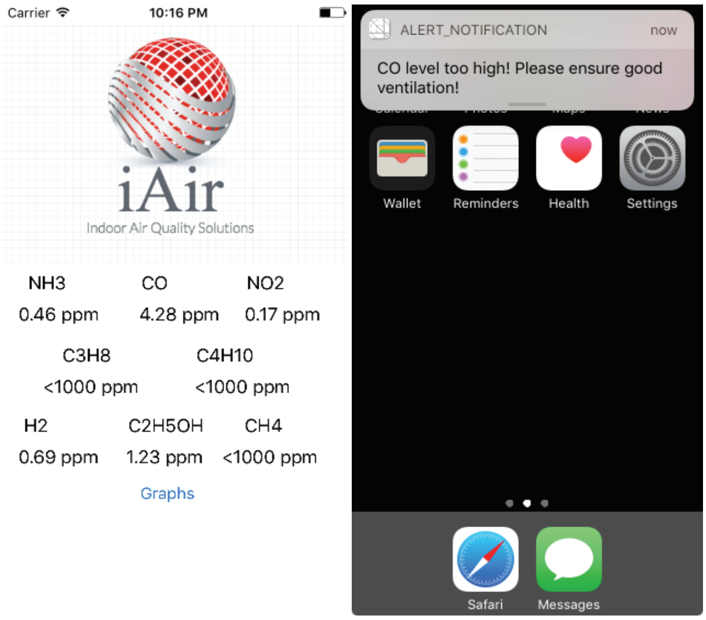


Figure 7. Installation schema.

Smartphones are an integral part of the daily routines of developed countries' individuals. The US has had exponential growth in the use of the smartphone. In fact, device ownership by adults was at 33% in 2011, 56% at the end of 2013, and 64% in early 2015 [63]. Also in the Netherlands, 70% of the total population and 90% of the adolescents own a smartphone [64]; in Germany, 40% of the people use a smartphone [65], and in the UK (United Kingdom), 51% of adults owned smartphones [66]. Smartphones incorporate excellent processing, storage, and sensing capabilities and can be used to provide intuitive access to the monitoring data. Therefore, a smartphone application, *iAirMobile*, was developed by the authors to provide intuitive and real-time access to the monitored data in numerical and chart forms (Figure 8).



(a) (b)

Figure 8. (**a**) *iAirMobile* last collected data; (**b**) example of an *iAirMobile* notification.

Table 4 presents several mobile applications for IAQ available for iOS and Android operating systems.

Table 4. IAQ mobile applications available on marketplaces.

Mobile Application	Air Pollutant	Android Support	iOS Support
Indoor Air Quality Sensor	IAQ index, temperature, CO_2, VOC, humidity	√	×
Air Mentor App	IAQ index, temperature, CO_2, VOC, relative humidity, PM	√	√
Acer Air Monitor	Temperature, PM, VOC, relative humidity	√	√
Air Quality Meter	IAQ index, PM	√	×
AQM Air Quality Monitor	Temperature, relative humidity, CO_2	√	×

PM: particulate matter; VOC: volatile organic compound; √: apply; ×: does not apply.

Compared with similar applications, the *iAirMobile* provides NH_3, CO, and NO_2 supervision for enhanced occupational health. These parameters are not monitored by any application described in Table 4. However, these parameters have an important role to provide safe and healthy spaces. The *iAir* solution is a multifeature tool for living environments' air quality analysis, and can support interventions to develop more productive indoor environments (Figure 8). The *iAir* solution has several advantages, such as modularity, small size, low-cost construction, and easy installation.

Particularly, IAQ monitoring is a trending topic for which some other low-cost and open-source monitoring systems that had been developed [67–73]. A summary of these studies is presented in Table 5.

Table 5. A summary of the similar types of research on IoT platforms for real-time IAQ monitoring.

Authors	MCU	Sensors	Architecture	Low Cost	Open-Source	Connectivity	Data Access	Easy Installation	Notifications
Srivatsa and Pandhare [67]	Raspberry Pi	CO_2	WSN/IoT	√	√	Wi-Fi	Web	×	×
Salamone et al. [68]	Arduino UNO	CO_2	WSN	√	√	ZigBee	×	×	×
Bhattacharya et al. [69]	Waspmote	CO, CO_2, PM, Temperature, Relative Humidity	WSN	×	√	ZigBee	Desktop	×	×
Salamone et al. [70]	Arduino UNO	Temperature, Relative Humidity, CO_2, Ligth, Air velocity	IoT	√	√	ZigBee/BLE	Mobile	×	×
Wang et al. [71]	Arduino	Temperature, Relative Humidity, CO_2	WSN	√	√	ZigBee	Desktop	×	×
Liu et al. [72]	TI MSP430	CO, Temperature, Relative Humidity	WSN	√	√	ZigBee	×	×	×
Kang and Hwang [73]	TI MSP430	CO, Temperature, Relative Humidity, VOC, PM	IoT	√	×	ZigBee	×	×	×

MCU: microcontroller; IoT: Internet of Things; WSN: wireless sensor networks; BLE: bluetooth low energy; √: apply; ×: does not apply.

Compared to other systems proposed by the authors of [68],[69], [71], and [72] based on wireless sensor networks (WSN), the IoT provides several advantages with regard to scalability and installation in indoor living environments, as is only necessary to configure the Wi-Fi internet connection and it is not required to configure the sensor nodes and coordinators. The *iAir* support notification features (Figure 8b) aim to provide people with timely information and provide them with the ability to react in real-time to significantly improve IAQ through the ventilation or deactivation of pollutant-producing equipment. When the parameters exceed the maximum value, the user is alerted to ensure proper ventilation. This feature is not implemented in any of the several similar solutions proposed and described in Table 3.

The incorporation of the ESP8266 module leads to several benefits. On one hand, the ESP8266 is a cost-effective microcontroller which can be used for processing and communication. On the other hand, this module can be configurated to work at 160 MHz of CPU clock speed, contrasting with the 16 MHz of the Arduino CPU clock speed.

The *iAir* Wi-Fi network configuration can be done in a few steps by the end user. When the *iAir* cannot access any memory stored in the Wi-Fi network, the ESP8266 turns to hotspot mode. At this stage, the end user can use a mobile device with Wi-Fi support, for example, a smartphone, to connect the hotspot and configure the SSID (service set identifier) and password of the desired Wi-Fi network through which the *iAir* is going to connect (Figure 9).

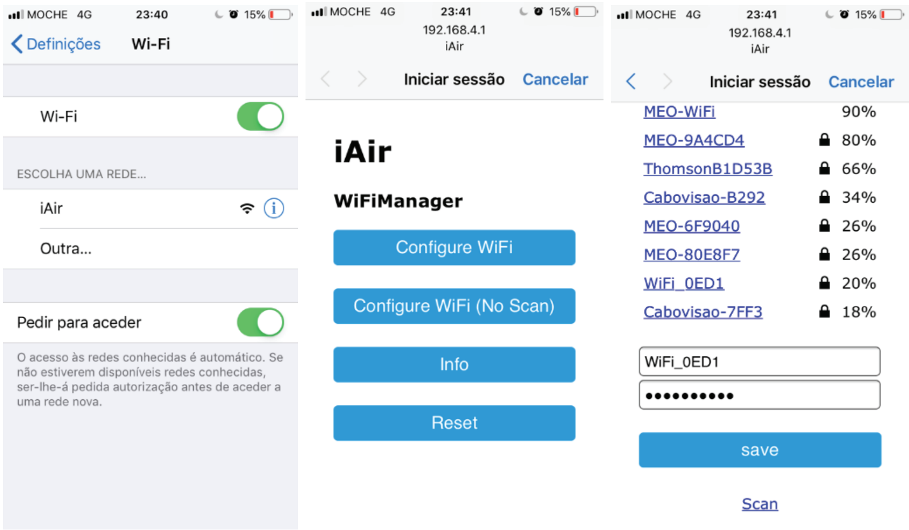


Figure 9. Wi-Fi configuration.

Compared to the majority of the state-of-the-art applications, the *iAir* supports an easy installation process which can be done by the end user. On one hand, the easy configuration feature avoids installation costs; for the majority of similar applications, installation must be done by qualified persons. On the other hand, this feature avoids the "invasion" of privacy related to the entry of unknown persons into the home of the end user.

Another important advantage of the *iAir* solution is the scalability associated with the modularity of the system. An installation can start using one *iAir* unit and new modules can be added over time, according to the needs of the environment.

The selection of the sensor was made focusing on the cost of the system, since the main objective was to test the functional architecture of the proposed solution. Considering that the system is intended to be used in indoor environments where there is available electricity, there was no great concern with the choice of ultra-low-power sensors when focusing on the research in real-time data collection and notification functionalities.

Radon is a radioactive pollutant that affects IAQ and cannot be detected by occupants because it is odorless and invisible. This contaminant can be originated from soil or building materials. Therefore, the authors plan to incorporate a radon sensor into *iAir* in future work.

5. Conclusion

This paper has presented a complete wireless solution composed of hardware for data collection and a mobile application for data consulting and notifications. This system aims to provide real-time IAQ monitoring using IoT architecture.

Compared to other systems, *iAir* possess several advantages, such as low cost, open-source technologies, easy installation and configuration, and full compatibility with all residential houses as long they have internet access and the owner has a smartphone. Another significant advantage of this system is the notification system that allows users to act in real-time to significantly improve IAQ through the ventilation or deactivation of pollutant-producing equipment.

AAL and the IoT can be the key to solve the independence problems of older adults. Combined with smart homes, smartphones, wearable technology, and IoT technologies, AAL systems give many opportunities to solve problems concerning emergencies, disabilities, and diseases. In spite of AAL systems' benefits and technology advancements, human care never should be replaced, because social relations and interactions are also fundamental. IoT systems and AAL will continue side by side to mutual contribute to scientific advances in assisted living, also allowing lowering of the cost of assisted living systems. Despite all the advantages in the use of IoT architecture, many open issues such as scalability, quality of service problems, and security and privacy still exist.

The results obtained are promising, representing a significant contribution to IAQ monitoring systems based on the IoT. Nevertheless, the proposed solution has some limitations. The *iAir* needs further experimental validation to improve system calibration and accuracy. In addition, hardware and software improvements have also been planned to adapt the system to specific cases or problems, such as supervising laboratory environmental conditions, schoolrooms, residential homes for old people, and hospitals.

In the future, the authors aim to develop a secure information-sharing solution with health professionals to support the diagnosis of health problems. The IAQ data can be extremely useful to provide support for clinical analysis by health professionals. By monitoring IAQ, we could detect unhealthy situations in real-time caused by, e.g., poor ventilation systems or inadequate intervention plans. The *iAir* solution is centred on the end user, aiming to provide ubiquitous access to their living environment health.

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References

1. United Nations. *World Population Ageing: 1950–2050*; Department of Economic and Social Affairs, Population Division, United Nations: United Nations: New York, NY, USA, 2002; pp. 11–13. ISBN 92-1-051092-5.
2. Centers for Disease Control and Prevention. The State of Aging and Health in America 2007. N. A. on an Aging Society, 2007. Available online: https://www.cdc.gov/aging/pdf/saha_2007.pdf (accessed on 20 December 2019).
3. Manogaran, G.; Chilamkurti, N.; Hsu, C.-H. Emerging trends, issues, and challenges in Internet of Medical Things and wireless networks. *Pers. Ubiquitous Comput.* **2018**, *22*, 879–882.
4. Manogaran, G.; Varatharajan, R.; Lopez, D.; Kumar, P.M.; Sundarasekar, R.; Thota, C. A new architecture of Internet of Things and big data ecosystem for secured smart healthcare monitoring and alerting system. *Future Gener. Comput. Syst.* **2018**, *82*, 375–387.
5. Rathore, M.M.; Paul, A.; Ahmad, A.; Chilamkurti, N.; Hong, W.-H.; Seo, H. Real-time secure communication for Smart City in high-speed Big Data environment. *Future Gener. Comput. Syst.* **2018**, *83*, 638–652.
6. Jo, D.; Kim, G.J. ARIoT: Scalable augmented reality framework for interacting with Internet of Things appliances everywhere. *IEEE Trans. Consum. Electron.* **2016**, *62*, 334–340.
7. Koleva, P.; Tonchev, K.; Balabanov, G.; Manolova, A.; Poulkov, V. Challenges in designing and implementation of an effective Ambient Assisted Living system. In Proceedings of the 2015 12th International Conference on Telecommunication in Modern Satellite, Cable and Broadcasting Services (TELSIKS), Serbia, Niš, 14–17 October 2015; pp. 305–308.
8. Atzori, L.; Iera, A.; Morabito, G. The Internet of Things: A survey. *Comput. Netw.* **2010**, *54*, 2787–2805.
9. Masse, R.A.C.; Ochoa-Zezzatti, A.; García, V.; Mejía, J.; Gonzalez, S. Saul Gonzalez Application of IoT with haptics interface in the smart manufacturing industry. *Int. J. Comb. Optim. Probl. Inform.* **2018**, *10*, 54–70.
10. Marques, G. Ambient Assisted Living and Internet of Things. In *Harnessing the Internet of Everything (IoE) for Accelerated Innovation Opportunities*; Cardoso, P.J.S., Monteiro, J., Semião, J., Rodrigues, J.M.F., Eds.; IGI Global: Hershey, PA, USA, 2019; pp. 100–115, ISBN 978-1-5225-7332-6.

11. Whitmore, A.; Agarwal, A.; Da Xu, L. The Internet of Things—A survey of topics and trends. *Inf. Syst. Front.* **2015**, *17*, 261–274.
12. Abdel-Basset, M.; Manogaran, G.; Mohamed, M. Internet of Things (IoT) and its impact on supply chain: A framework for building smart, secure and efficient systems. *Future Gener. Comput. Syst.* **2018**, *86*, 614–628.
13. Hong, S.; Kim, Y.; Kim, G.J. Developing Usable Interface for Internet of Things (IoT) Security Analysis Software. In *Human Aspects of Information Security, Privacy and Trust*; Tryfonas, T., Ed.; Springer International Publishing: Cham, Switzerland, 2017; Volume 10292, pp. 322–328, ISBN 978-3-319-58459-1.
14. Diro, A.A.; Chilamkurti, N. Distributed attack detection scheme using deep learning approach for Internet of Things. *Future Gener. Comput. Syst.* **2018**, *82*, 761–768.
15. Hsu, C.-H. Internet of People and situated computing. *Pers. Ubiquitous Comput.* **2016**, *20*, 847–849.
16. Zhou, Z.; Feng, J.; Tan, L.; He, Y.; Gong, J. An Air-Ground Integration Approach for Mobile Edge Computing in IoT. *IEEE Commun. Mag.* **2018**, *56*, 40–47.
17. Walsh, P.J.; Dudney, C.S.; Copenhaver, E.D. *Indoor Air Quality*; CRC Press: Boca Raton, FL, USA, 1983; ISBN 0-8493-5015-8.
18. Jones, A.P. Indoor air quality and health. *Atmos. Environ.* **1999**, *33*, 4535–4564.
19. Wei, S.; Ning, F.; Simon, F.; Kyungeun, C. A Deep Belief Network for Electricity Utilisation Feature Analysis of Air Conditioners Using a Smart IoT Platform. *J. Inf. Process. Syst.* **2018**, *14*, 162–175.
20. Pitarma, R.; Marques, G.; Ferreira, B.R. Monitoring Indoor Air Quality for Enhanced Occupational Health. *J. Med Syst.* **2017**, *41*, 23.
21. Marques, G.; Pitarma, R. Health informatics for indoor air quality monitoring. In Proceedings of the 2016 11th Iberian Conference on Information Systems and Technologies (CISTI), Gran Canaria, Spain, 15–18 June 2016; AISTI: Rio Tinto, Portugal, 2016; pp. 1–6.
22. Pitarma, R.; Marques, G.; Caetano, F. Monitoring Indoor Air Quality to Improve Occupational Health. In *New Advances in Information Systems and Technologies*; Rocha, Á., Correia, A.M., Adeli, H., Reis, L.P., Mendonça Teixeira, M., Eds.; Springer International Publishing: Cham, Switzerland, 2016; Volume 445, pp. 13–21, ISBN 978-3-319-31306-1.
23. Marques, G.; Pitarma, R. Smartphone Application for Enhanced Indoor Health Environments. *J. Inf. Syst. Eng. Manag.* **2016**, *4*, 9.
24. Marques, G.; Pitarma, R. Monitoring Health Factors in Indoor Living Environments Using Internet of Things. In *Recent Advances in Information Systems and Technologies*; Rocha, Á., Correia, A.M., Adeli, H., Reis, L.P., Costanzo, S., Eds.; Springer International Publishing: Cham, Switzerland, 2017; Volume 570, pp. 785–794, ISBN 978-3-319-56537-8.
25. Marques, G.; Pitarma, R. Monitoring and control of the indoor environment. In Proceedings of the 2017 12th Iberian Conference on Information Systems and Technologies (CISTI), Lisbon, Portugal, 21–24 June 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1–6.
26. Feria, F.; Salcedo Parra, O.J.; Reyes Daza, B.S. Design of an Architecture for Medical Applications in IoT. In *Cooperative Design, Visualization, and Engineering*; Luo, Y., Ed.; Springer International Publishing: Cham, 2016; Volume 9929, pp. 263–270, ISBN 978-3-319-46770-2.
27. Ray, P.P. Internet of things for smart agriculture: Technologies, practices and future direction. *J. Ambient Intell. Smart Environ.* **2017**, *9*, 395–420.
28. Matz, J.R.; Wylie, S.; Kriesky, J. Participatory Air Monitoring in the Midst of Uncertainty: Residents' Experiences with the Speck Sensor. *Engag. Sci. Technol. Soc.* **2017**, *3*, 464–498.
29. Demuth, D.; Nuest, D.; Bröring, A.; Pebesma, E. The AirQuality SenseBox. In Proceedings of the EGU General Assembly Conference Abstracts, Vienna, Austria, 7–12 April 2013; Volume 15.
30. Marques, G.; Pitarma, R. An indoor monitoring system for ambient assisted living based on internet of things architecture. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1152.
31. Salonen, H.J.; Pasanen, A.-L.; Lappalainen, S.K.; Riuttala, H.M.; Tuomi, T.M.; Pasanen, P.O.; Bäck, B.C.; Reijula, K.E. Airborne Concentrations of Volatile Organic Compounds, Formaldehyde and Ammonia in Finnish Office Buildings with Suspected Indoor Air Problems. *J. Occup. Environ. Hyg.* **2009**, *6*, 200–209.

32. Felix, E.P.; Cardoso, A.A. A method for determination of ammonia in air using oxalic acid-impregnated cellulose filters and fluorimetric detection. *J. Braz. Chem. Soc.* **2012**, *23*, 142–147.
33. Mostafa, E.; Hoelscher, R.; Diekmann, B.; Ghaly, A.E.; Buescher, W. Evaluation of two indoor air pollution abatement techniques in forced-ventilation fattening pig barns. *Atmos. Pollut. Res.* **2017**, *8*, 428–438.
34. Tuomainen, M.; Tuomainen, A.; Liesivuori, J.; Pasanen, A.-L. The 3-year follow-up study in a block of flats - experiences in the use of the Finnish indoor climate classification. *Indoor Air* **2003**, *13*, 136–147.
35. Lindgren, T. A case of indoor air pollution of ammonia emitted from concrete in a newly built office in Beijing. *Build. Environ.* **2010**, *45*, 596–600.
36. Jarnstrom, H.; Saarela, K.; Kalliokoski, P.; Pasanen, A. Reference values for indoor air pollutant concentrations in new, residential buildings in Finland. *Atmos. Environ.* **2006**, *40*, 7178–7191.
37. Bull, K..; Sutton, M. Critical loads and the relevance of ammonia to an effects-based nitrogen protocol. *Atmos. Environ.* **1998**, *32*, 565–572.
38. Webb, J.; Menzi, H.; Pain, B.F.; Misselbrook, T.H.; Dämmgen, U.; Hendriks, H.; Döhler, H. Managing ammonia emissions from livestock production in Europe. *Environ. Pollut.* **2005**, *135*, 399–406.
39. Saha, C.K.; Zhang, G.; Kai, P.; Bjerg, B. Effects of a partial pit ventilation system on indoor air quality and ammonia emission from a fattening pig room. *Biosyst. Eng.* **2010**, *105*, 279–287.
40. Ernst, A.; Zibrak, J.D. Carbon Monoxide Poisoning. *N. Engl. J. Med.* **1998**, *339*, 1603–1608.
41. Clardy, P.F.; Manaker, S.; Perry, H. Carbon monoxide poisoning. UpToDate. Literature review current through: Apr 2017.
42. Haines, D. Carbon monoxide poisoning. *Med. -Leg. J.* **2016**, *84*, 59–59.
43. Weaver, L.K. Carbon Monoxide Poisoning. *N. Engl. J. Med.* **2009**, *360*, 1217–1225.
44. Blumenthal, I. Carbon Monoxide Poisoning. *J. R. Soc. Med.* **2001**, *94*, 270–272.
45. Frampton, M.W.; Morrow, P.E.; Cox, C.; Gibb, F.R.; Speers, D.M.; Utell, M.J. Effects of Nitrogen Dioxide Exposure on Pulmonary function and Airway Reactivity in Normal Humans. *Am. Rev. Respir. Dis.* **1991**, *143*, 522–527.
46. Strand, V.; Rak, S.; Svartengren, M.; Bylin, G. Nitrogen dioxide exposure enhances asthmatic reaction to inhaled allergen in subjects with asthma. *Am. J. Respir. Crit. Care Med.* **1997**, *155*, 881–887.
47. Mills, I.C.; Atkinson, R.W.; Kang, S.; Walton, H.; Anderson, H.R. Quantitative systematic review of the associations between short-term exposure to nitrogen dioxide and mortality and hospital admissions. *BMJ Open* **2015**, *5*, e006946.
48. Folinsbee, L.J. Does nitrogen dioxide exposure increase airways responsiveness? *Toxicol. Ind. Health* **1992**, *8*, 273–283.
49. Belanger, K.; Gent, J.F.; Triche, E.W.; Bracken, M.B.; Leaderer, B.P. Association of Indoor Nitrogen Dioxide Exposure with Respiratory Symptoms in Children with Asthma. *Am. J. Respir. Crit. Care Med.* **2006**, *173*, 297–303.
50. Pilotto, L.; Douglas, R.; Attewell, R.; Wilson, S. Respiratory effects associated with indoor nitrogen dioxide exposure in children. *Int. J. Epidemiol.* **1997**, *26*, 788–796.
51. Favarato, G.; Anderson, H.R.; Atkinson, R.; Fuller, G.; Mills, I.; Walton, H. Traffic-related pollution and asthma prevalence in children. Quantification of associations with nitrogen dioxide. *Air Qual. Atmos. Health* **2014**, *7*, 459–466.
52. Hamra, G.B.; Laden, F.; Cohen, A.J.; Raaschou-Nielsen, O.; Brauer, M.; Loomis, D. Lung Cancer and Exposure to Nitrogen Dioxide and Traffic: A Systematic Review and Meta-Analysis. *Environ. Health Perspect.* **2015**, *123*, 1107–1112.
53. Amegah, A.K.; Jaakkola, J.J. Household air pollution and the sustainable development goals. *Bull. World Health Organ.* **2016**, *94*, 215–221.
54. Lee, S.C.; Li, W.-M.; Ao, C.-H. Investigation of indoor air quality at residential homes in Hong Kong—Case study. *Atmos. Environ.* **2002**, *36*, 225–237.
55. Kandpal, J.B.; Maheshwari, R.C.; Kandpal, T.C. Indoor air pollution from domestic cookstoves using coal, kerosene and LPG. *Energy Convers. Manag.* **1995**, *36*, 1067–1072.
56. Cardiopulmonary Outcomes and Household Air Pollution Trial (CHAP) Trial Investigators; Fandiño-Del-Rio, M.; Goodman, D.; Kephart, J.L.; Miele, C.H.; Williams, K.N.; Moazzami, M.; Fung, E.C.; Koehler, K.; Davila-Roman, V.G.; et al. Effects of a liquefied petroleum gas stove intervention on

pollutant exposure and adult cardiopulmonary outcomes (CHAP): Study protocol for a randomized controlled trial. *Trials* **2017**, *18*, 518.
57. Anenberg, S.C.; Schwartz, J.; Shindell, D.; Amann, M.; Faluvegi, G.; Klimont, Z.; Janssens-Maenhout, G.; Pozzoli, L.; Van Dingenen, R.; Vignati, E.; et al. Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls. *Environ. Health Perspect.* **2012**, *120*, 831–839.
58. Logue, J.M.; McKone, T.E.; Sherman, M.H.; Singer, B.C. Hazard assessment of chemical air contaminants measured in residences: Hazard assessment of indoor air contaminants. *Indoor Air* **2011**, *21*, 92–109.
59. Spengler, J.; Sexton, K. Indoor air pollution: A public health perspective. *Science* **1983**, *221*, 9–17.
60. SGX Sensortech MICS-6814 Data Sheet. Available online: https://sgx.cdistore.com/datasheets/sgx/1143_Datasheet%20MiCS-6814%20rev%208.pdf (accessed on 18 January 2019)
61. Espressif Systems ESP8266EX Datasheet. 2018. Available online: https://espressif.com/sites/default/files/documentation/0a-esp8266ex_datasheet_en.pdf (accessed on 23 January 2019).
62. Neuburg, M. *iOS 7 Programming Fundamentals: Objective-c, xcode, and cocoa Basics*; O'Reilly Media, Inc.: Sebastopol, CA, USA, 2013; ISBN 1-4919-4690-3.
63. Müller, H.; Gove, J.L.; Webb, J.S.; Cheang, A. Understanding and Comparing Smartphone and Tablet Use: Insights from a Large-Scale Diary Study. In Proceedings of the Annual Meeting of the Australian Special Interest Group for Computer Human Interaction, Parkville, Australia, 7–10 December 2015; ACM: New York, NY, USA, 2015; pp. 427–436.
64. van Deursen, A.J.A.M.; Bolle, C.L.; Hegner, S.M.; Kommers, P.A.M. Modeling habitual and addictive smartphone behavior. *Comput. Hum. Behav.* **2015**, *45*, 411–420.
65. Montag, C.; Błaszkiewicz, K.; Sariyska, R.; Lachmann, B.; Andone, I.; Trendafilov, B.; Eibes, M.; Markowetz, A. Smartphone usage in the 21st century: Who is active on WhatsApp? *BMC Res. Notes* **2015**, *8*, 331.
66. Pearson, C.; Hussain, Z. Smartphone Use, Addiction, Narcissism, and Personality: A Mixed Methods Investigation. *Int. J. Cyber Behav. Psychol. Learn.* **2015**, *5*, 17–32.
67. Srivatsa, P.; Pandhare, A. Indoor Air Quality: IoT Solution. Available online: http://www.ijrat.org/downloads/ncpci2016/ncpci-46.pdf (accessed on 22 December 2018).
68. Salamone, F.; Belussi, L.; Danza, L.; Galanos, T.; Ghellere, M.; Meroni, I. Design and Development of a Nearable Wireless System to Control Indoor Air Quality and Indoor Lighting Quality. *Sensors* **2017**, *17*, 1021.
69. Bhattacharya, S.; Sridevi, S.; Pitchiah, R. Indoor air quality monitoring using wireless sensor network. In Proceedings of the 2012 Sixth International Conference on Sensing Technology (ICST), Kolkata, India, 18–21 December 2012; IEEE: Piscataway, NJ, USA, 2012; pp. 422–427.
70. Salamone, F.; Belussi, L.; Danza, L.; Ghellere, M.; Meroni, I. Design and Development of nEMoS, an All-in-One, Low-Cost, Web-Connected and 3D-Printed Device for Environmental Analysis. *Sensors* **2015**, *15*, 13012–13027.
71. Wang, S.K.; Chew, S.P.; Jusoh, M.T.; Khairunissa, A.; Leong, K.Y.; Azid, A.A. WSN based indoor air quality monitoring in classrooms; In *AIP Conference Proceedings*; AIP Publishing: Melville, NY, USA, 2017; p. 020063.
72. Liu, J.-H.; Chen, Y.-F.; Lin, T.-S.; Lai, D.-W.; Wen, T.-H.; Sun, C.-H.; Juang, J.-Y.; Jiang, J.-A. Developed urban air quality monitoring system based on wireless sensor networks. In Proceedings of the 2011 Fifth International Conference on Sensing Technology (ICST), Palmerston North, New Zealand, 28 November–1 December 2011; IEEE: Piscataway, NJ, USA, 2011; pp. 549–554.
73. Kang, J.; Hwang, K.-I. A Comprehensive Real-time Indoor Air-Quality Level Indicator. *Sustainability* **2016**, *8*, 881.

Chapter 6

Conclusions and Future Work

This chapter presents the main conclusions that result from the research work described in this thesis. Furthermore, it discusses research topics related to the work developed in doctoral research, which may be addressed in the future.

1. Final Conclusions

AAL and IoT may be the key to solving the problems of independence of the most debilitated population. Combined with smart homes, smartphones, wearable technology, IoT technologies, and AAL systems offer numerous opportunities to solve problems related to emergencies, disabilities, and diseases. Nevertheless, the benefits and technological advances of AAL systems, personal care must never be replaced because social relationships and interactions are also fundamental. The IoT and AAL systems will continue to contribute side by side to provide scientific advancements to reduce the cost of AAL systems. Despite all the advantages of healthcare systems, several open issues continue to exist, such as availability, reliability, mobility, performance, scalability, and interoperability. As the evolution of the society will not stop, these will be ongoing open issues because the use case scenarios will not remain static.

IoT offers new methods, architectures, and solutions for enhanced living environments and should be faced with an opportunity to design healthcare systems that can collect essential data to support medical diagnostics and promote health and well-being. New IoT architectures and methods should provide smartphone and smartwatch compatibility, as these devices are seen today as an essential part of daily life and are perceived as extremely important and useful instruments to provide notifications and active coaching to improve their users' health and consequently, public health. Today, mobile devices incorporate a diversity of sensors that can be used to provide real-time monitoring solutions and data collection to support medical treatments.

The main focus of this thesis is the design of new IoT architectures and methods for enhanced living environments. The proposed methods are low-cost, easy to install, modular, and scalable using wireless technologies and mobile computing. Smartphones are an integral part of the daily routine of developed countries and incorporate excellent processing, storage, and sensing capabilities. Furthermore, mobile computing can be used to provide intuitive access to monitoring data. Therefore, the proposed methods support mobile Frameworks not only for data analysis and visualization but also for notifications.

The primary purpose of the thesis is the definition and design of modular and scalable IoT methods for air quality monitoring to provide enhanced living environments. The proposed architectures incorporate various concepts from the acquisition, processing, storage, analysis, and visualization of data. These methods offer an alert management Framework that notifies the user in real-time and ubiquitously in poor indoor quality scenarios. Moreover, these methods support several notification methods, such as real-time notifications for smartphones using SMS and e-mail. This real-time notification architecture offers several advantages when the goal is to achieve effective changes for enhanced living environments. The proposed architectures are reliable and use cost-effective sensors to enable high-scale implementation.

Furthermore, the proposed methods incorporate advanced data analysis and visualization tools and allow ubiquitous data access anywhere, anytime. These architectures allow addressing numerous open issues in today's societies regarding emergencies, disabilities, diseases, and remote monitoring. These methods ensure cost-effective and efficient indoor monitoring and provide enhanced data consulting methods by supporting mobile and web software for data analytics. The data collected could be accessed in real-time for enhanced living environments. These methods provide a stream of data that can be used by the occupants and the building manager to provide interventions in useful time to increase the indoor quality to promote occupational health and well-being.

The main objective was divided into four intermediate objectives that began with the revision of the state-of-the-art. This review aimed to correctly understand and evaluate the IoT paradigm in terms of the various opportunities for numerous applications, particularly enhanced living environments and healthcare systems. The review of the state-of-the-art lead to the design and implementation of an IoT architecture for PM air quality monitoring, a Web Framework for data consultation and history, and remote notifications presented in Chapter 3. As the third intermediate objective, the development of a Framework for the evaluation of indoor air quality by monitoring the carbon dioxide concentration levels. This Framework consists of a monitoring system, Web software, and mobile application for data consulting and several types of alerts such as SMS, e-mail, and remote notifications through mobile computing technologies, described in Chapter 4. In Chapter 5, an IoT architecture is proposed for the collection of several air quality parameters using a Cloud service. This Framework combines sensitivity, flexibility, and measurement accuracy in real-time, allowing a significant evolution of current air quality monitoring systems. The results show that this system provides easy, intuitive, and fast access to air quality data as well as essential notifications in poor air quality situations to provide real-time intervention for enhanced living environments.

The objectives of this thesis were achieved with the design of new IoT architectures and methods for enhanced living environments. These architectures present new, cost-effective, scalable, and modular methods that support mobile computing technologies for notifications purposes and data visualization and analysis methods that effectively contribute to enhanced living environments and occupational health.

2. Future Work

The proposed IoT architectures for enhanced living environments are modular and scalable monitoring systems that incorporate various concepts from acquisition, processing, storage, analysis, and visualization of data. Data consulting and real-time notifications allows the building manager to identify patterns of unhealthy in order to plan interventions for enhanced living environments. Also, this data can be shared with medical teams to assist with diagnostics.

Nevertheless, the proposed solution has some limitations. The proposed architectures need further experimental validation to improve system calibration and accuracy. Hardware and software improvements have also been planned to adapt the system to specific cases or problems, such as schoolrooms, residential homes for older adults, and hospitals. In the future work, several enhancements are planned regarding the development of a secure information-sharing solution with health professionals to support the diagnosis of health problems. The air quality data can be beneficial to provide support for clinical analysis by health professionals. By monitoring indoor air quality, we could detect unhealthy situations in real-time caused by, *e.g.*, weak ventilation systems or inadequate intervention plans.

In the near future, there will be legislation to enforce real-time monitoring of buildings for enhanced living environments, and consequently to decrease the healthcare costs with treatments that can be avoided by living under high indoor quality levels. Furthermore, architectures such as the proposed in this thesis not only will contribute to enhanced living environments but also be an integral part of our daily routine.