Interoperability Between IEEE 802.11e and HSDPA: Challenges From Cognitive Radio

Orlando Cabral, João M. Ferro and Fernando J. Velez

Abstract In this chapter we propose a scenario for interoperability between High-Speed Downlink Packet Access (HSDPA) and Wi-Fi. This scenario involves the end-user travelling in public transportation system and requesting multimedia services to the operator. The inter-operability between HSDPA and Wi-Fi (IEEE 802.11e standard) Radio Access Tecnologies (RAT) is firstly addressed, a topology in which the user has access to both RATs was considered, together with a Common Radio Resource Management (CRRM) to manage the connections. We reached the conclusion that the CRRM enables to increase the system throughput when the load thresholds are set to 0.6 for HSDPA and 0.53 for Wi-Fi. Then, spectrum aggregation is implemented in HSDPA. A Resource Allocation (RA) algorithm, allocates user packets to the available radio resources (in this case Node Bs operating at 2 and a 5 GHz are available) in order to satisfy user requirements. Simulation results show that gains up to 22% may be achieved. We have also sought the most efficient way to manage routing packets inside the Wi-Fi network. The proposal which uses links with higher throughputs enables to reach the best results, with gains up to 300% in the packet delivery ratio. Finally, we discuss the challenges that need to be addressed in order to materialise the envisaged cognitive radio scenario in public transportation.

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1 Introduction

In this chapter we address a network of wireless networks, consisting of a backbone infrastructure provided by High-Speed Downlink Packet Access (HSDPA) radio towers hierarchically bonded with a flexible wireless ad hoc network running IEEE 802.11e standard. The purpose of this hybrid network is to serve users with high-quality video and audio content, using the already existing infrastructure. We first discuss the interoperability between HSDPA and Wi-Fi, and provide a brief presentation of the simulator built for this study. Then, we discuss spectrum aggregation, and some results obtained by that simulator in an HSDPA/HSDPA scenario. Two Node Bs (NBs) operating at 2 GHz and 5 GHz are available, and the operator automatically switches the user between them. In the context of the Wi-Fi network, we studied the effects of changing the routing metrics in the service quality for an ad hoc network, mostly the number of packets delivered and latency. With this study we managed to find the best approach, which will be used to compute the paths for the hierarchical HSDPA/Wi-Fi scenario that is being suggested, and which will be simulated in the future.

2 HSDPA/Wi-Fi interoperability

In recent years, cooperation has been gaining an increased interest in the context of wireless networks. The definition of Wireless Mesh Networks (WMN) and the upcoming standard IEEE 802.11s demonstrates the interest in this type of networks [1]. The cooperation between heterogeneous networks is also an hot topic, like demonstrated by several IST projects such as CAUTION [2] or AROMA [3].

In our scenario, the mesh network involves the use of two different radio access technologies, the HSDPA and the Wi-Fi ones. In this section, we present our study on cooperation and coexistence for these networks.

2.1 Interoperability between HSDPA and Wi-Fi

To study the cooperation between HSDPA and Wi-Fi (IEEE 802.11e) Radio Access Technologies (RATs), we use a Common Radio Resource Management (CRRM) algorithm for RAT selection, based on the load, between these two technologies in a common coverage area. The scenario under study is presented in Fig. 1.

An IP-based core network is assumed to act as the bridge between Wi-Fi and HSDPA. Within this bridge, a cooperative networking entity that logically communicates with HSDPA and Wi-Fi (referred as the CRRM entity) is responsible for:

- gathering system and user specific information;
- processing this information according to operator specific criteria;

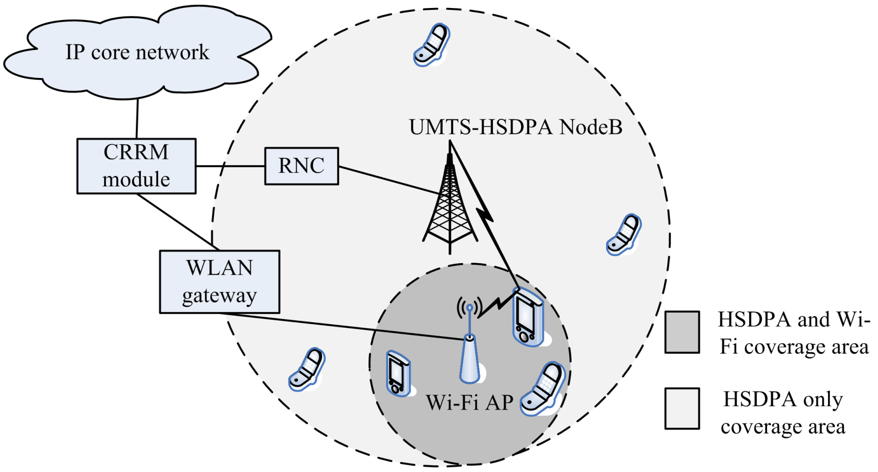

Fig. 1 Area covered by HSDPA and Wi-Fi in the interoperability scenario.

- triggering a new handover events according to the load balancing criteria.

Moreover, it is assumed that a common operator deploys both systems, or those systems from different operators share a service level agreement.

The scenario addresses the delivery of near real time video (NRTV) services that can be streamed either over the HSDPA or Wi-Fi systems. The end user is currently subscribing to an IPTV service, which is also currently being delivered over the Wi-Fi hotspot. This initial connection was chosen since it was deemed to be the most "fitting" network for the requested service. An example is shown in Fig. 1. The operator, which is monitoring both networking entities, observes a sudden surge in Wi-Fi subscribers overloading the Wi-Fi network, while UMTS is under-loaded, and handling the usual voice services. The CRRM entity may decide that it would be more efficient to move some of the Wi-Fi users to the UMTS-HSDPA network, since this leads to better QoS provisioning, and exploits the existing network capacity in a more efficient way. As a consequence, the CRRM triggers a series of handover events that ensure an even load distribution across both networks. When a user is triggered for handover, the multi-mode terminal initiates a new connection with UMTS-HSDPA, terminating the existing connection with the Wi-Fi system. The handover events occur in a seamless manner.

2.2 *Simulation results*

The interoperability scenario is based on a test field covered by the HSDPA and Wi-Fi technologies, assuming high-priority NRTV video traffic characterised by the 3GPP model [4] at 64 kbps . The generation of NRTV calls is modelled by a Poisson distribution, while the call duration is exponentially distributed with an average of 180 s. The scenario is deployed in our custom-made simulator, created by the IST-UNITE project [5]. Details on the HSDPA simulator structure and features are presented in [6], while details for the IEEE 802.11e package are given in [7]. The main simulation parameters are presented in Table 1. Since the Wi-Fi network supports a larger throughput than HSDPA, we started it with four FTP, four voice and three NRTV users. This enables to load the network from the beginning of the simulation, and reach a stable point without having an excessively long simulation time.

Table 1 Values for the simulations.

Parameter	HSDPA	Wi-Fi
Mode	FDD (Tx mode)	EDCA (MAC Tx mode)
Scheduler	MaxCI	Round-Robin
Link Adaptation	BLER max = 10%	Similar to [8]
Radio propagation model	3GPP indoor + FF	ITU 2 GHz propagation (Path Loss)
Cell type	Omni-directional	Omni-directional
Number HS- PDSCH (data codes)	15	–
Bandwidth	5 MHz	Variable with the user SNR
Initial number of users	20	11

Users are distributed uniformly in the area of HSDPA coverage. This area is larger than the Wi-Fi zone. The HSDPA cell radius (*R*) is variable so that, in the best case situation, Wi-Fi covers 50% of the HSDPA area, whilst in the worst case it covers just 13% of it. It is assumed that NRTV users prefer to use HSDPA. If the load surpasses a given threshold the value of the user suitability is calculated to help on RAT selection decisions. If a user is more suited to be within the Wi-Fi, then the CRRM entity may decide to move him to Wi-Fi, depending on the coverage. To analyse the benefits obtained by having CRRM procedures, two scenarios were considered:

- No vertical handover;
- The users position is fully known and only the HSDPA users that are within Wi-Fi zone may be switched (from HSDPA to Wi-Fi).

All the results obtained are presented with a 95% confidence interval. Figure 2 presents results for the throughput without considering the CRRM entity, as a function of the total number of users for a cell radius of 50 meters (*R*=50 m). The Over the Air (OTA) throughput represents the number of bits that have been transmitted in the cell, the Service (Serv) throughput represents the number of bits that have been transmitted and correctly received (without packet errors), and the Quality-of-Service (QoS) throughput represents the number of bits correctly received (without packet errors) within the allowed delay. Details on the formulation of these evaluation metrics can be found in [9].

After 37 users (11 within Wi-Fi, and 26 within HSDPA), the QoS throughput starts to decrease. The number of unsatisfied users for the NRTV is given by:

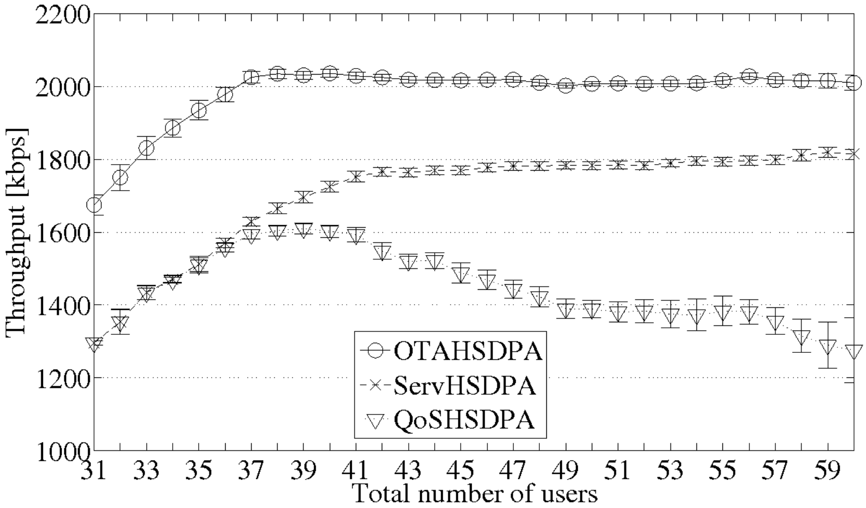

Fig. 2 Throughput without CRRM entity exploring the diversity gain for *R*=50 m.

$$\frac{64 \times number\ of\ users - QoS_{throughput}}{64} \quad (1)$$

When 60 users are active (11 in Wi-Fi and 49 in HSDPA), 28 users (approximately 57%) are unsatisfied, since they are being served with poor quality, e.g., long queueing time.

The objective is to reach the optimal load balance between the two RATs. By analysing the values of the load when the QoS starts to decrease in each system, we get to the conclusion that the most appropriate load thresholds are $LTh_0 = 0.6$ for HSDPA (RAT 0) and $LTh_1 = 0.53$ for Wi-Fi (RAT 1). Figure 3 presents the results for the throughput in HSDPA for $LTh_0 = 0.6$.

Other values were considered for the load threshold. However, using $LTh_0 = 0.7$ (with results presented in Fig. 4) and $LTh_0 = 0.8$ (with results presented in Fig. 5) resulted in users exceeding the QoS delay threshold, i.e., 300 ms. For example, considering $LTh_0 = 0.8$ and 60 users, around 350 kbps are delivered above the delay threshold, corresponding to 10% of unsatisfied users.

In Wi-Fi, the service class that suffers the most degradation by adding NRTV users is the background one, since it is the one with less priority. The delays suffered either by the voice or video service classes are always lower than the respective thresholds specified in the literature, i.e., 30 ms for voice and 300 ms for video. For the background application, we considered a delay threshold of 10 s. Our results show that this delay threshold is overcome when there are more than 13 users in the Wi-Fi system, as shown in Fig. 6. This corresponds to a Wi-Fi load threshold of $LTh_1 = 0.53$.

Figure 7 compares the overall QoS throughput with the offered load in the presence and absence of the CRRM. It increases with the offered load until the HSDPA

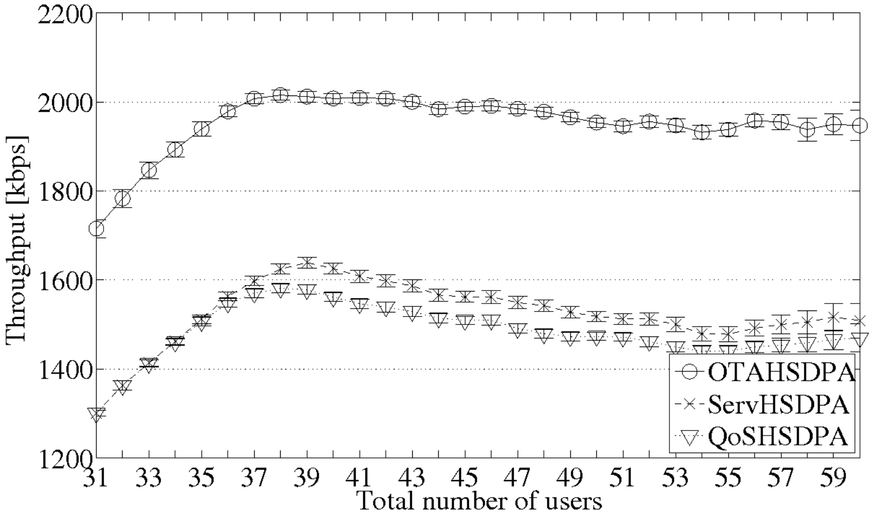

Fig. 3 Throughput in HSDPA with the CRRM entity exploring the diversity gain, for *R*=50 m.

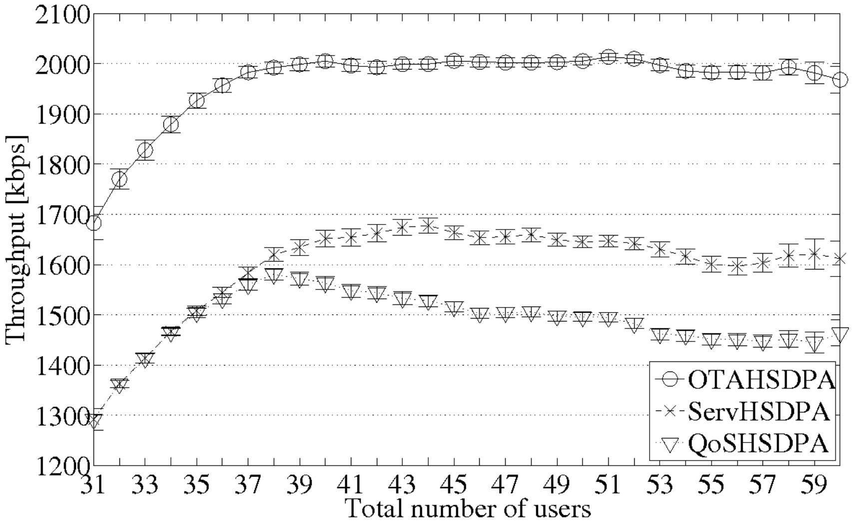

Fig. 4 Throughput in HSDPA with the CRRM entity exploring the diversity gain, for *R*=50m for $LTh_0 = 0.7$.

system capacity is reached. By taking the available modulation and coding schemes (MCS) into account, the maximum load accommodated by HSDPA is around 1.6 Mbps (as shown in Fig. 2).

In Fig. 7, the throughput without considering the CRRM entity accounts for the HSDPA traffic plus the NRTV Wi-Fi traffic, which includes three initial users from

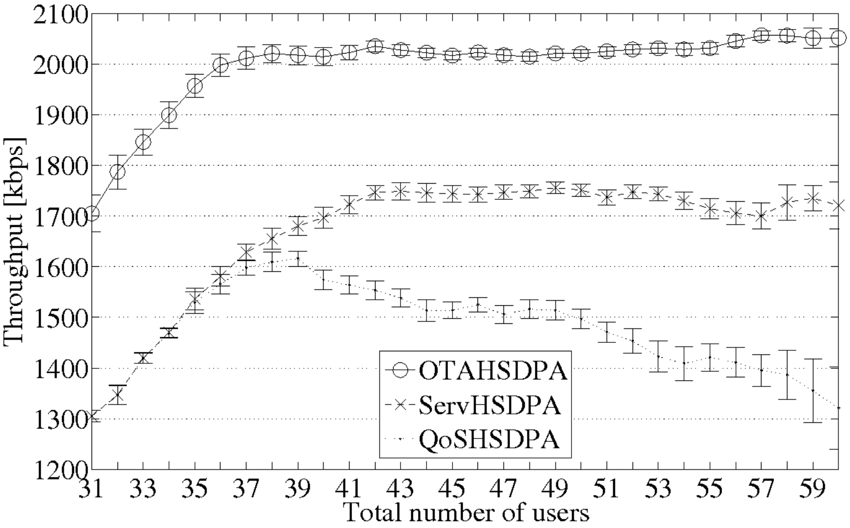

Fig. 5 Throughput in HSDPA with the CRRM entity exploring the diversity gain, for *R*=50m for $LTh_0 = 0.8$.

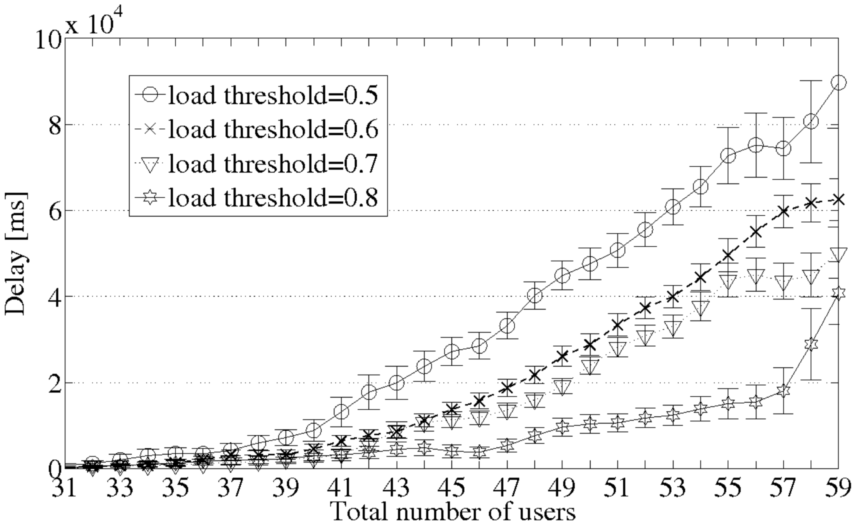

Fig. 6 Delay for background traffic as a function of the total number of users, for several values of load threshold.

Wi-Fi. As the offered load increases, the QoS throughput raises up to 1.7 Mbps. However, from this point forward, it starts to decrease down to 1.5 Mbps. This effect is due to the use of the "max C/I" scheduler. The presence of the CRRM avoids this decrease. If the optimal load threshold is reached ($LTh_0 = 0.6$), by comparing

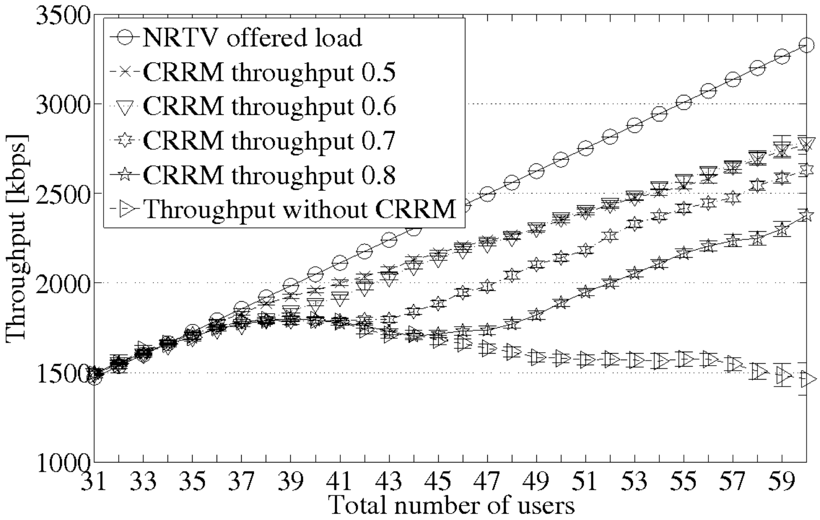

Fig. 7 Comparison of the total throughput with and without the CRRM entity exploring the diversity gain.

the throughput between the presence and absence of CRRM, the observable gain is 2700/1500=80% (at 60 users). The use of lower load thresholds is not advised, since it causes the Wi-Fi system to overload "faster", causing problems to the background traffic.

2.3 Lessons learned from RAT selection

In this section we found the optimal load threshold that maximises the total QoS throughput for the cooperation between two wireless networks of different technologies: HSDPA and Wi-Fi. Simulation results have shown that optima load thresholds in this interworking scenario are 0.6 for HSDPA and 0.53 for Wi-Fi. This corresponds to a throughput CRRM gain of 80%, with 60 users.

3 Spectrum aggregation between the 2 GHz and 5 GHz bands in HSDPA

Cognitive Radio (CR) refers to the way network nodes change its transmission frequency in order to avoid interference, or to increase the amount of bandwidth it can use. It requires that the node is equipped with the hardware necessary to transmit in the frequencies to be used, which is paid back in terms of QoS.

In our hypothetical scenario, we consider that several NBs are deployed in the scenario, each one uses its own frequency band. In this section, we provide results for testing a topology just considering two NBs. In this scenario, an operator has an exclusive license at 2 GHz, but also has access to the 5 GHz band. The latter is shared with other operators. The operator's management entity defines which frequency to assign to each user, according to its capacity and users requesting the service.

3.1 Problem formulation

In our simulations, we consider the same type of Radio Access Technology (RAT) for both frequency bands, trying to prove that integration of dynamic spectrum use and Radio Resource Management (RRM) techniques leads to an increase of performance. The system prefers to use the 2 GHz band, which is the one allocated exclusively to the operator. The use of the 5 GHz band must be negotiated with the rest of the operators. We focus not on how the negotiation with other operators is made, but how, after having gained access to a certain (fixed) frequency pool in the 5 GHz band, to allocate the users in the available bands. The performance gains are analysed in terms of data throughput. The total throughput is calculated as a function of the radio channel qualities for each user in the considered bands. The Channel Quality Indicator (CQI) depends on the path loss, which depends not only on the distance from the NB, but also on the carrier frequency adopted. The operator applying Multi-Band Scheduling (MBS) will reach considerable improvements when the users have heterogeneous spatial distribution in the cell (variable distances from the NB), and different channel qualities in the considered spectrum bands.

The problem of scheduling the users into two bands (2 GHz and part or all of the frequency pool at 5 GHz) can be formulated as an Integer Programming (IP) optimisation problem [10]. The Profit Function (PF) to be maximised via a single objective maximisation problem is the total throughput of the operator (fairness and QoS requirements of the service classes are not considered). However, multiple objectives can be easily introduced and implemented in the problem, such as maximising the total throughput while minimising the QoS satisfaction indexes for each service class [11]. Solving Multiple Objectives General Assignment Problem (MO-GAP) can be very difficult and usually the objectives are combined together via a linear combination, called "scalarisation" [12]. The GMBS problem can be solved considering users with the added capability of transmitting and receiving in multiple frequency simultaneously (the user equipment has multiple transceivers) or when it can just chose one band among all the bands in the network and choosing one of the transceiver configurations available at the radio. In both cases, we have a formulation of an IP problem with different constrains, as described in [13].

3.2 System modelling

The Resource Allocation (RA) component is responsible for allocating the available radio resources to the user traffic in a effective manner, and includes a scheduling mechanism, link adaptation, code allocation policy, and an Hybrid Automatic Repeat Request (H-ARQ) scheme to improve service throughput for users at the cell edge. The HSDPA network was simulated using the simulator described in section 2.2, with the following functionalities and characteristics:

- Multi omni-directional cell deployment model, hexagonal cells, consisting in three tiers, for interference purposes (results are presented only for the centre cell);
- NRTV streaming traffic model from [4] at 64 kbps;
- RRM schemes, including of Adaptive Modulation and Coding (AMC), *n*-parallel channel H-ARQ using chase combining and Round-robin scheduling algorithm;
- ITU-based radio propagation models: the channel loss between the user and the NB is modelled by path loss, shadowing loss by log-normal distribution and fast fading using approximated Jakes model [14];
- The interference in the user is calculated considering the signal strength received from the neighbour NBs and the thermal noise;
- The simulator as an input uses a BLER table provided by the link layer simulations of [15].

Each Time Transmission Interval (TTI) is associated with a sub-frame duration that corresponds to an HSDPA frame duration of 2 ms, with three time slots of 0.67 ms each. The HSDPA physical layer [16] provides 15 orthogonal codes available for data transmission within a sub-frame. The available data rates are summarised in Table 2. For each CQI identifier, the modulation scheme, the block sizes, the number of transport channels and the transport rate are given. The CQI is a mapping of the averages of the Signal-to-Interference Ratio (SIR) recorded over time. The direct mapping between CQI_{bu} and the $R(CQI_{bu})$ can be expressed as:

$$R(CQI_{bu}) = \begin{cases} 188.5\ if\ CQI_{bu} = 5 \\ 198.0\ if\ CQI_{bu} = 8 \\ 331.9\ if\ CQI_{bu} = 15 \\ 716.8\ if\ CQI_{bu} = 22 \end{cases} \tag{2}$$

3.3 Resource Allocation

The RA algorithm allocates the user packets to the available radio resources in order to satisfy the user requirements, and to ensure efficient packet transport to maximise spectral efficiency. The RA is an entity within the set of RRM algorithms that should have inherent tuning flexibility to maximise the spectral efficiency of the system

Table 2 Transport block size and bit rate associated to CQI.

CQI	Modulation	Transport block size [bits]	Number of HS-PDSCH	R(CQI) [kbps]
CQI 5	QPSK	377	1	188.5
CQI 8	QPSK	792	2	396.0
CQI 15	QPSK	3319	5	1659.5
CQI 22	16-QAM	7168	5	3584.0

for any type of traffic QoS requirements. The adopted RA algorithm maps packets of variable size into variable length radio blocks for transmission over the PHY layer, and the length is dependent on the channel quality. The following events are performed:

1. User packets awaiting transmission are prioritised according to the scheduling algorithm criteria;
2. A CQI identifier is selected according to the link adaptation algorithm, using the available CQI options from the PHY layer;
3. The scheduler calculates the number of MAC transport blocks required to transmit the scheduled packet. The number of channels is calculated according to:

$$Number\ of\ blocks = \left\lceil \frac{PacketSize}{BlockSize(CQI)} \right\rceil \quad (3)$$

   where $\lceil x \rceil$ is the lowest integer higher or equal to x;
4. An idle ARQ channel j is selected to hold and manage the ARQ transmission;
5. The packet is transmitted and received at the user equipment. Soft retransmissions are combined with previous packet transmissions (chase combining) and the ARQ messages are generated accordingly. These are then signalled to the NB, and the ARQ processes are released if the messages are positive acknowledgements (ACKs).

3.4 2 GHz and 5 GHz usage under a CRRM approach

The 2 GHz and 5 GHz frequency bands are characterised over the same HSDPA architecture by assuming the model summarised in Table 3, which is according to [17].

By adopting a CRRM [18] to manage the extra resources, we propose to use HSDPA at 2 GHz and at 5 GHz. The CRRM entity keeps track of the CQI in both frequencies. This scenario is presented in Fig. 8, where the darker areas represent better coverage.

Table 3 Parameters and models used for 2 GHz and 5 GHz bands.

Carrier frequency	2 GHz	5 GHz
Bandwidth	5MHz	5MHz
Path loss model:	$128.1 + 37.6\log(d_{[km]})$	$141.52 + 28\log(d_{[km]})$
Shadowing decorrelation length	5m	20m

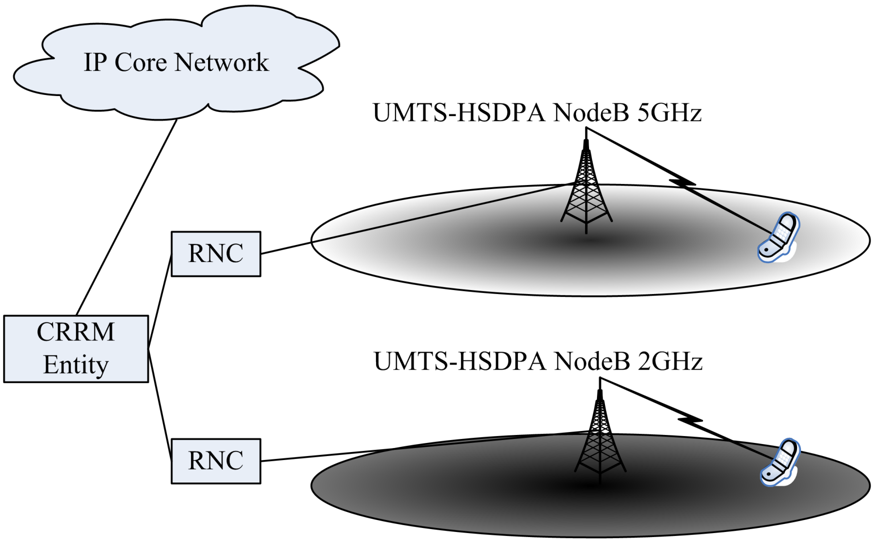

Fig. 8 CRRM in the context of two separated frequencies.

3.5 Results

For the results we focus on the throughput of the network, which is the total number of bits that have been transmitted and correctly received by all users in the cell. Users are displaced in the cell with an uniform distribution within a distance of 900 m so that both frequencies can cover the whole cell. The NRTV calls are modelled by a Poisson distribution, the call duration is exponentially distributed with an average of 180 s. The bars on the curves represent a 95% confidence interval, which is achieved by running at least 50 simulations for each case. In some cases, additional runs were made to achieve the required accuracy.

Figure 9 shows the results for the throughput without MBS. In this case, the two bands are managed separately, the call requests are divided into the two bands. It is not possible to switch a service from one band to the other. The "Overall Serv" throughput is the sum of the service throughput in both frequency bands. The traffic requirement is the traffic required to satisfy all the users (i.e., the NRTV required rate – 64 kbps – multiplied by the number of users in the system). From the number of users presented in the abscissas, half of them are operating in the 2 GHz, and the others in the 5 GHz band.

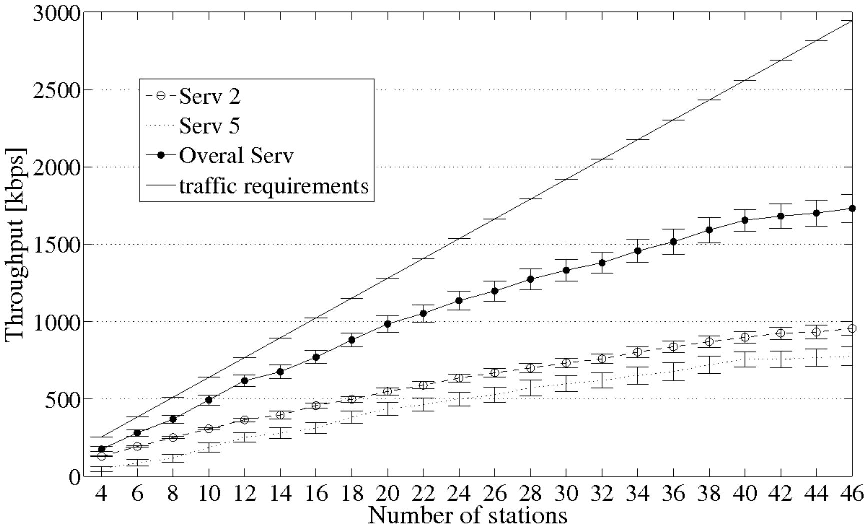

Fig. 9 Average throughput without MBS.

Figure 10 shows the results when the MBS algorithm is applied. The CRRM entity can decide on which band the user can be allocated in order to maintain control over the network resources. After 18 users, as the 2 GHz band has reached a threshold for the load, the MBS algorithm handles the user allocation.

When the MBS is applied over the two bands, a higher throughput is achieved due to the switching of the users based on their respective channel qualities. The curves from Fig. 11 enable a comparison between the results with and without the use of MBS. it is shown that the MBS algorithm increases the performance of the system. This is more evident when more than 24 stations are in the scenario topology, corresponding to a gain up to 400 kbps. This happens because, up to a given load, both bands can deal with the required traffic. However, after this value for the load, retransmissions start to make the difference.

3.6 Summary and conclusions

In this section we analysed how CR can be used in the context of our work. The use of the same RAT with widely separated spectrum resources can increase the system performance without generating interference and obtaining a gain of 22%. This gain was obtained by optimally managing radio resources based a integer optimisation procedure, where inputs come from active sensing on all the probable useful

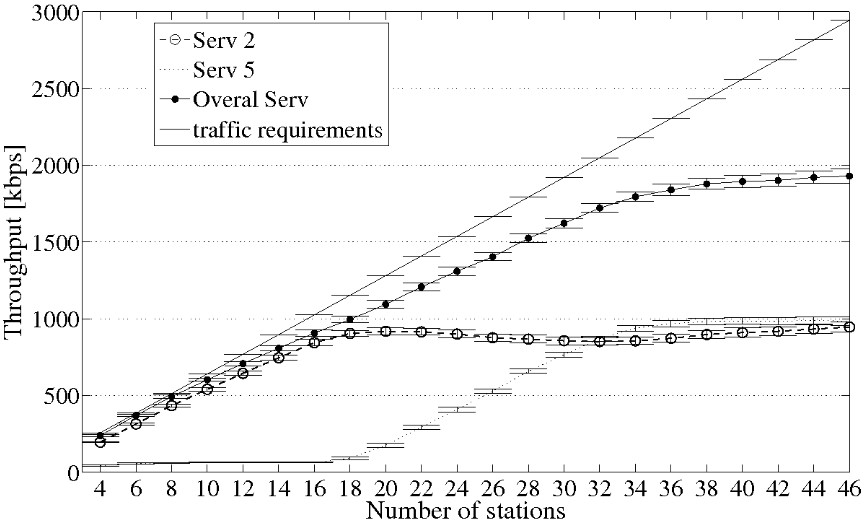

Fig. 10 Average throughput with MBS.

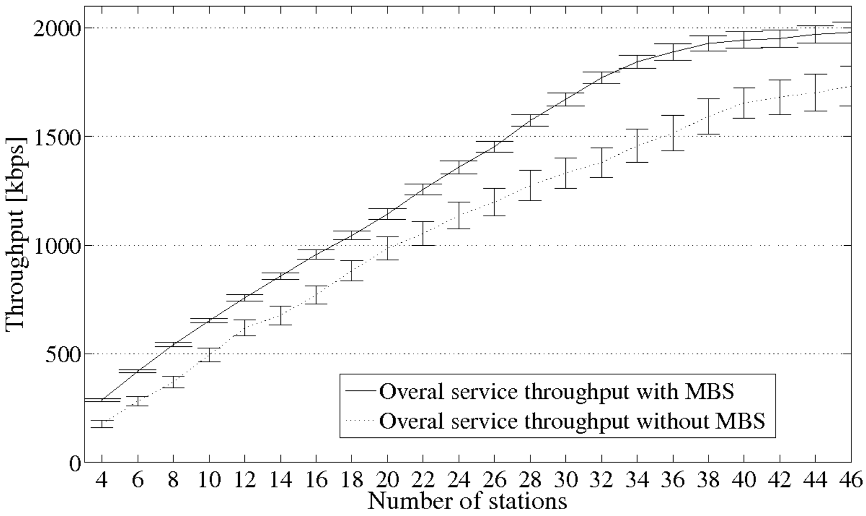

Fig. 11 Service throughput in the presence and absence of MBS.

spectrum and past receptions. This however occurs at the cost of some additional resources, a common radio resource management entity that manages resource, and compatible radios at the user side.

4 IEEE 802.11e ad hoc networking

In this section, we present several approaches to determine the best path for packets flowing in an IEEE 802.11e ad hoc network. Unlike the infrastructure mode, the IEEE 802.11e ad hoc mode does not use an entity responsible for managing the communications within the network. As so, the role of the Access Point (AP) is distributed by all the stations that are part of the network. Hence, it is up to each station which receives a packet to know to where it should be forwarded to. This is known as the routing problem, and its optimisation is very important so that packets flow through the best path possible, enabling them to reach destination efficiently (meaning arriving safely and with a low delay). If the routing does not work efficiently, packets will start to get lost or taking longer paths and/or entering loops, which generates problems to the upper layers. There are several approaches that can be used in order to obtain the best path for the packets. In our work, all the stations have global knowledge of the network, meaning that they know all the connections that exist between the stations. This is done by impelling each station to perform a transmission in full power, and make all the others read the received Signal-to-Interference-Noise-Ratio (SINR). This gives information not only about which neighbors each station has, but also what type of modulation and coding schemes can be used in each link. We use that information to compute the routing table for all stations, whose entries indicate the next hop for each destination.

In our study, we focus not on how the information about the links quality is spread across the network, but on the best way to, given a table of the connections between all the stations, determine which path the packets should take to arrive promptly at the destination. For this purpose, we address the optimisation problem in two different ways: the empirical approach, and the Genetic Algorithm (GA) one. In the empirical approach, we manually define the cost functions for each link. In turn, GAs are an optimisation approach that enables to reach the optimal solution without having to study the entire space of possible solutions.

All the results presented in this section were obtained by running the simulations in the custom-made IEEE 802.11e simulator from [19]. This simulator was developed by the Instituto de Telecomunicações – Covilhã Delegation team, and tightly follows the amendment “e” of IEEE 802.11 standard, which embraces the support for Quality-of-Service in these networks. This is achieved by mapping all packets into one of the four existing access categories (VI, VO, BK, and BE), and unequally treating them according to this classification. This means that the MAC layer scheduling will give, for example, priority to a packet marked as video over another one marked as background.

4.1 Empirical approach

In our first approach, we manually assign a cost to each link. Then, Dijkstra’s Algorithm (DA) [20] is run in a table containing the cost of all links, which allows for getting the least-cost path from each station to all the others. This information is inserted in the routing table which, for each pair source/destination, indicates the ID of the "next hop". For the first tests we wanted to verify how the signal strength in each link could be used to compute the best path. If a link has a strong signal, it is more robust to the outside interference, and it can use a modulation (and coding rate) that allows for transmitting at a higher data rate, allowing for faster transmissions, as shown in Table 4. However, strong signal can only be achieved if the stations are close to each other, which means that the overall progress of the packet towards the destination will be slower than if a longer link was used. Of course, the use of a longer link implies a lower data rate, and since the signal is weaker, more interference will exist.

Table 4 The relation between the SINR, modulation and data rate.

Mode	Modulation	Code rate	Min. SINR	Link throughput [Mbit/s]
1	BPSK	1/2	4.1	6
2	BPSK	3/4	-	9
3	QPSK	1/2	7.9	12
4	QPSK	3/4	11.0	18
5	16-QAM	1/2	14.8	24
6	16-QAM	3/4	17.8	36
7	64-QAM	2/3	22.8	48
8	64-QAM	3/4	24.2	54

In order to define if the best approach was to use longer, robuster, or intermediary links, we proposed the following cost function:

$$cost = abs\left(data\_rate - setpoint\right) \tag{4}$$

The setpoints used are presented in Table 5.

Table 5 The setpoints in study.

Function	Setpoint [Mbit/s]	Privileges
Alfa	$(data\_rate + 1)$	Paths with less hops/longer links
Beta	21	Intermediary links
Gama	30	Intermediary links
Delta	56	Robuster links

Three types of traffic sources were chosen. The traffic sources parameters are presented in Table 6, as well as the Access Categories (AC) of each type of traffic. Seven traffic streams were put in the scenario, one VI, three VO, and three BK streams. VI and BK traffic are unidirectional, while VO is bidirectional.

Table 6 Traffic parameters.

AC	Voice (VO)	Video (VI)	Background (BK)
Packet size	1280 bit	10240 bit	18430 bit
Packet interval	20 ms	10 ms	12.5 ms

Simulations were run for a random deployment of 30 stations on a 150 × 150 m^2 field. The obtained results for a simulation time of 15 seconds are summarised in Table 7. These results are only for the video traffic that is being generated in station 3 and has station 10 as the destination.

Table 7 Results for each cost function.

Function	Latency [ms]	Packets delivered	Packets delivered [%]
Alfa	6547	74	74/1500=0.049(3)
Beta	5675	197	197/1500=0.131(3)
Gama	5704	98	98/1500=0.065(3)
Delta	5361	282	282/1500=0.188

From the results, one can conclude that the approach which privileges links with higher SINR allows to deliver more packets and with a lower latency.

4.2 Genetic Algorithms approach

In the second approach, we replaced the determination of the best path for the GAs approach. The challenges presented by GAs are the following ones:

Codification: the chromosomes are the paths. A chromosome is a vector of integers that represents the set of node IDs through which a packet has to go from the origin to the destination. The first locus of the chromosome is the origin while the last one is the destination. The ones in the middle have an order that the packet being transmitted needs to follow. For example, the chromosome [A N1 N2 B] establishes that a packet going from A to B has to go first to node N1, then to N2, and finally to B. The maximum size of the chromosomes is the maximum number of stations in the scenario.

Fitness metric: the fitness represents chromosome quality. it must reflect as precisely as possible the quality of a chromosome. In our case, the fitness value has some noise provided by the randomisation features of the simulator. To reduce this noise and not discard a good chromosome (or use a bad chromosome as a parent more often), we evaluate a chromosome with a given degree of freedom. In this work, the fitness value is provided by the number of packets delivered in a given period. However, we could have considered the delay or any other metric for the fitness parameter, and the algorithm would work the same way.

Population initialisation: an heuristic method in which the costs of the links in the DA follow an exponential distribution, was used.

Selection procedure: the selection procedure chooses the chromosomes to be parents of an offspring. The parents with best fitness will give the best offspring [21]. Therefore, if we want to increase the fitness while getting closer to the optimal solution, the chromosomes with higher fitness should have higher probability of being selected, i.e., the selection procedures focus on the exploitation of promising areas of the solution space. From the several tested the Rank Selection was the one that presented better results. It involves the following steps:

1. The chromosomes are ranked according to the fitness;
2. The top 1/4 of the chromosomes are selected;
3. To generate offspring, two chromosomes are selected randomly from the set found in step 2.

Crossover between genes: two chromosomes are two solutions for the problem. The crossover brings a new solution derived from them. In our case, the crossover is done by exchanging partial route of two chosen chromosomes (paths).

Mutations: a mutation is performed by randomly changing the genes in the chromosome. The mutation in our case is not a standard case since we cannot change a given locus randomly without any constraint; otherwise we could get a path without connection. Mutation is only possible if, when requested, there is an alternative path to the one being used from the locus over which the mutation was requested.

Results for the Rank/List and Tournament selection algorithms were obtained from three seconds simulations, and are presented in Fig. 12 for the same topology as in the previous test. Several simulation runs were considered for the List selection (dashed lines) and for the Tournament selection (solid lines) algorithms.

It can be observed that the List selection algorithm presents better results than the Tournament selection algorithm, as it delivers more packets. The List selection algorithm also converges faster than the Tournament selection one. The List selection algorithm delivers approximately 16% of the packets, but its performance is not as high as the Delta function from the empirical approach, which delivers 18.8% of the packets (but it can be improved).

4.3 Conclusions and future work

The goal of the routing algorithms proposed in this work was to find a path that delivers the highest number of packets in an IEEE 802.11e ad hoc network with the lowest delay. This optimisation was tested for a single video stream whilst considering background and voice traffic streams, to increase the network load. A novel hybrid method to initialise the GA chromosomes was proposed. The simulations with the best initial population size (40) and the best selection algorithm (List/Rank)

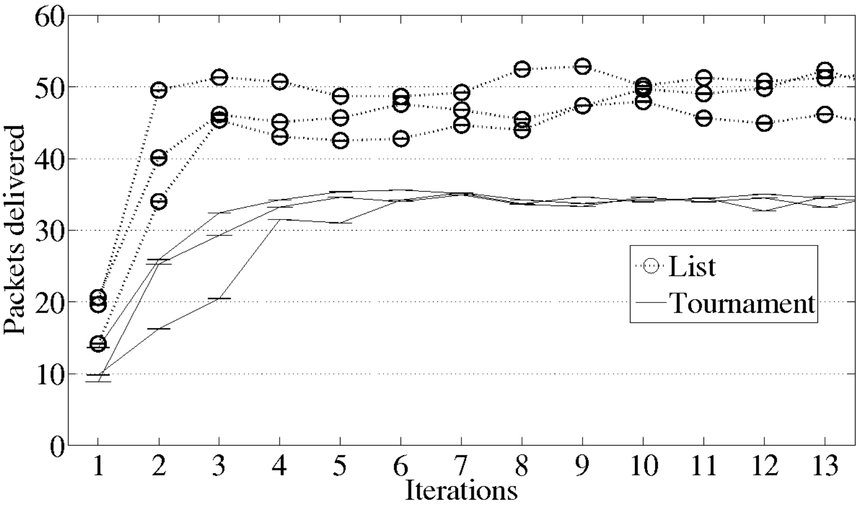

Fig. 12 Packets delivered in topology 1 with the Tournament selection (solid lines) and List selection (dashed lines) algorithms.

always converge to a single solution. In this case, the GA approach did not manage to reach better results than the best empirical one, but from our simulations in more random generated topologies in most of the cases GA outperformed the other approach. However, we are only present the initial results in this chapter. As a future work, we intend to use the QoS feature of the simulator to attribute a different cost function to different traffic types. For example, a function that delivers more packets, but with larger delay, can be used for background traffic, while another with more packet drops, but with lower delay, can be used to compute the path for video traffic. In this case, the fitness function of GA could account for more than the packets delivered like a weighted function that accounts for packets delivered and other metrics like jitter, and delay that will enhance the quality of experience of the users. More topologies will also be tested, to check which metrics are more suitable.

5 Challenges for hierarchical HSDPA/Wi-Fi scenario

In our envisaged scenario we are looking for a way to provide the best service to the end user. One possibility for our scenario is depicted in Fig. 13.

The user is requesting NRTV while moving on a public transportation service. This can be a bus moving inside the town, or a train in the suburbs. On the one hand, the mobility (which is higher in the train scenario) is presented as a great challenge, since it requires frequents handover as the user travels outside the area that was covered by the antenna he was connected to. On the other hand, the natural

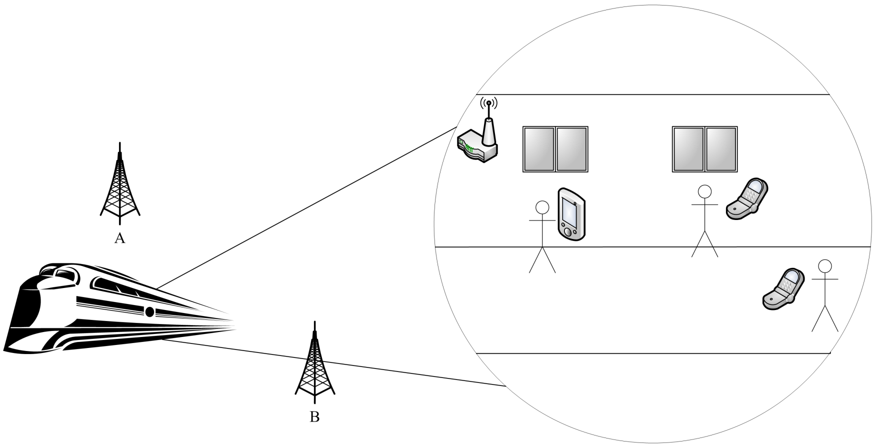

Fig. 13 The scenario under study. Users get access to services from a Wi-Fi or an HSDPA connection, depending on which one is more suitable.

and man-made (e.g., buildings) obstacles interfere with the signal, also requiring a well planned handover strategy since a massive building can temporary block the connection between the user and his serving antenna. The service must be provided with QoS assurance, meaning that the video displayed on the user terminal must have enough quality (which include acceptable throughput and no service interrupts). For that purpose, it can be served by an HSDPA NB, or by a nearby Wi-Fi hotspot, or even another user that is closer, depending on which can provide the (best) service. The train has an efficient outdoor receiver that can better receive the signal than any of the user terminals inside, and is connected to the Wi-Fi hotspot in the coach. If the train is passing some problematic spots, e.g., very tall buildings or mountain area, the user terminal may start getting a lousy signal from the NB, and to ensure the QoS in can be switched to the Wi-Fi network, which can get a clear signal from outside. For users that are far from the wireless router, for example if they are in another coach, the connection can be made by using another terminal as a relay.

Nowadays, the technology allows mobile phones to have 3G, Wi-Fi, and even WiMAX communications capabilities, all integrated into one equipment. As so, the availability of different technologies in the end user equipment is not an issue for our scenario. The true issue is how to decide to which technology should the terminal be connected to, and how to make the different RATs cooperate and not interfere. This is integrated in the larger challenge which is the routing one: the packets have to be routed through several hops, each one using its own technology, before arriving into the core network. We designate these routes as cognitive paths (CPs). The entity that controls the flow of information and define the CPs must have accurate and up-to-date information regarding all the users in the network, their connections quality and user requirements. This involves a good amount of information flowing to the routing coordination entity, and enough processing capacity required to it, in order to efficiently serve all the network. The algorithm that generates the CPs may involve complex calculations if the network has to serve a large number of users and several connection options. However, nowadays both software and hardware solutions are enough developed to materialise this scenario.

6 Conclusions

In this chapter we aimed to provide the best service possible to a user requesting high quality and time dependent services, such as video or voice. The core of the service is provided by standard HSDPA NBs, whose coverage is improved indoor by using Wi-Fi ad hoc connections. The Wi-Fi uses the standard IEEE 802.11 with its amendment "e" to prioritise the delay sensitive traffic. The solution presented is not yet implemented nor simulated, but we provide isolated tests for each component of the system.

First we studied the inter interoperability between these two wireless technologies. Since the operation is performed in different frequency bands, these technologies can co-exist without interfering with each other. From the tests run in our simulator, we demonstrated that the Wi-Fi can improve the coverage of the HSDPA without the need of a complex management system, providing a better service for the users.

Then we studied the HSDPA system in the context of Cognitive Radio, by using two NBs operating at different frequencies. The operator has access to the 2 GHz and the 5 GHz bands. The system automatically chooses the frequency to serve the user. It was shown that having a secondary band can increase the throughput of the system, and serve more users.

In the Wi-Fi ad hoc network, the goal was to find the path that delivered the highest number of packets and with the lowest delay. The optimisation was tested for a video stream, whilst considering background and voice traffic streams to increase the network load. We first defined our cost functions manually, but ended-up by using an automatic optimisation procedure in the form of GAs. Choosing the path that minimises the delay whilst maintaining the delivery ratio is very important to provide QoS to the user, and our optimal approach manages to reach these two objectives.

The main challenge for our cognitive radio scenario for public transportation is to discover and maintain the paths between the service provider and the end user, which we call the cognitive paths. We have shown that, isolated, each piece of the network can be optimised to provide the best performance possible, and we expect to use the optimisation performed in the global management entity. The simulator to be used is being conceived and adapted for the tests, and we expect to obtain results soon.

Acknowledgements The authors would like to acknowledge the following projects who provided financial support: IST-UNITE (a Specific Targeted Research Project supported by the European 6th

Framework Programme, Contract number IST-FP6-STREP-026906), Marie Curie European Reintegration Grant PLANOPTI (Planing and Optimization for the Coexistence of Mobile and Wireless Networks Towards Long Term Evolution, FP7-PEOPLE-2009-RG), UBIQUIMESH (Cross-Layer Optimization in Multiple Mesh Ubiquitous Networks ref PTDC/EEA-TEL/105472/2008), CROSSNET (a Portuguese Foundation for Science and Technology, FCT, POSC project with FEDER funding), Marie Curie Intra-European Fellowship OPTIMOBILE (Cross-layer Optimization for the Coexistence of Mobile and Wireless Networks Beyond 3G, FP7-PEOPLE-2007-2-1-IEF), and Projecto de Re-equipamento Científico REEQ/1201/EEI/2005 (an FCT project). João Ferro and Orlando Cabral acknowledge the Ph.D. grants from FCT ref. SFRH/BD/36742/2007 and SFRH/BD/28517/2006, respectively. Authors also acknowledge the COST Action 2100 - Pervasive Mobile & Ambient Wireless Communications, the Portuguese project Smart-Clothing, Valdemar Monteiro, Jonathan Rodrigues, Filippo Meucci and Albena Mihovska.

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