

Intra-Operator Spectrum Sharing Concepts for Energy Efficiency and Throughput Enhancement

Invited Paper

Oliver Holland¹, Alireza Attar², Orlando Cabral³, Fernando J. Velez³, and A. Hamid Aghvami¹

¹ Centre for Telecommunications Research, King's College London
London, United Kingdom
{oliver.holland, hamid.aghvami}@kcl.ac.uk

² Department of Electrical and Computer Engineering, University of British Columbia
Vancouver, BC, Canada
attar@ece.ubc.ca

³ Instituto de Telecomunicações, DEM
Universidade da Beira Interior
Covilhã, Portugal
{orlandoc, fjb}@ubi.pt

Abstract—Cognitive radio and other dynamic spectrum sharing paradigms have enjoyed the limelight recently for their potential to realize a number of benefits for communications systems. The majority of investigated solutions thus far have looked at primary/secondary access and sharing of spectrum among different spectrum owners. In contrast, this paper investigates solutions for spectrum sharing among different bands owned by the same entity, such as a mobile operator, and demonstrates considerable potential for such solutions to improve power efficiency for the network and to increase throughput. The paper utilizes four means to achieve this potential: spectrum sharing through the opportunistic movement of users between bands allowing radio network equipment in other bands to be switched off when possible, spectrum sharing to opportunistically improve links' propagation characteristics therefore reducing necessary transmission power, better interference management in spectrum sharing to reduce necessary transmission power, and the opportunistic aggregation of spectrum bands to increase achievable throughput. Power consumption reductions of over 50%, both in terms of mains power draw and in terms of necessary transmission power, are demonstrated. Moreover, throughput enhancements of up to 20% are achieved.

Keywords: *dynamic spectrum access, green communications*

I. INTRODUCTION

Dynamic spectrum access has thus far primarily been investigated in the context of different spectrum owners accessing each others' spectrum, or in other primary/secondary access paradigms such as "cognitive radio". However, given different spectrum bands being owned by the same entity but

being designated for different usage purposes, the dynamic sharing of the spectrum among those purposes is also of considerable research interest. The ability for a mobile operator, for example, to dynamically share and optimally use its available spectrum bands among its provided networks presents considerable opportunity to reduce power consumption in running its networks and services, and also gives scope to increase throughput compared with the sum throughput that could be achieved given the operator managing its networks independently at the designated bands.

This paper investigates various methods for such spectrum sharing opportunity to reduce mains power consumption, necessary transmission power, and improve throughput for mobile networks. Section II discusses and assesses the use of intra-operator resource sharing to dynamically move users between networks at different frequencies, thus allowing radio network equipment to be opportunistically powered down when possible. Section III briefly discusses and assesses the potential for radio links to be dynamically moved to better frequencies to reduce necessary transmission power through propagation improvement. Section IV concentrates on interference management in intra-operator sharing to save power, and Section V investigates spectrum aggregation of 2GHz and 5GHz bands in a WiMAX scenario, showing considerable throughput increase potential. Finally, Section VI concludes and discusses possible areas for future work.

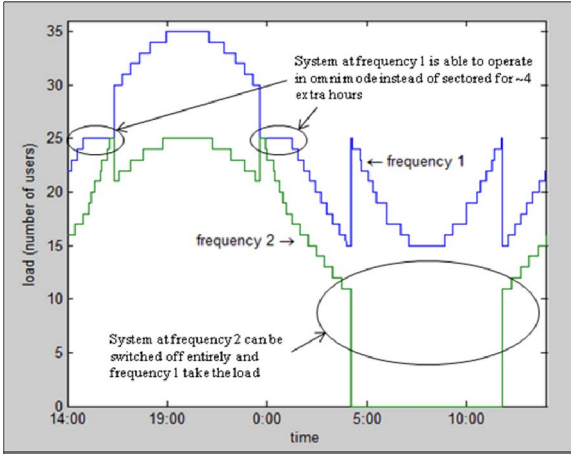


Figure 1. Example of traffic load variations under the cosine traffic representation applying the opportunistic network equipment powering down solution, where the busy load for frequency 1 is 35 users, the busy load for frequency 2 is 25 users, and quiet loads are 25% of the respective busy loads.

II. OPPORTUNISTIC REALLOCATION OF USERS BETWEEN BANDS TO POWER DOWN RADIO NETWORK EQUIPMENT

The opportunistic powering down or entering into stand-by of radio network equipment through reallocating users to other spectrum bands at times of low load is extremely promising as it implies a guaranteed *from the mains* power saving. This section attempts to assess this saving; further information on the concept and the savings therein can be obtained from [1].

There are two possibilities considered here: (i) turning off (cells in) one network or spectrum band entirely at that time/location, through traffic being sufficiently carried by a single network or spectrum band in omnidirectional mode, and (ii) removing sectorization for a network, e.g., using spare capacity of one network/frequency, to cover the required drop in load of another frequency/network in order for that other frequency/network to operate in omnidirectional mode instead of tri-sectorized mode. Figure 1 exemplifies these options for two collocated cells concurrently operating at different frequencies, though depicting the resulting traffic loads.

To exemplify the performance of the suggested approach for a case where an operator might be running the same system at different spectrum bands, we assume two GSM-like networks with parameterizations as given in Table 1. Our utilized traffic model assumes that the average traffic load over a 24hr period might be seen as varying according to a scaled (in both time and amplitude) and shifted sine or cosine cycle [2], [3]. Given this, the average cell load at time t ,

$$L(t) = \left\| \frac{BusyLoad + QuietLoad}{2} + \frac{BusyLoad - QuietLoad}{2} \cos(2\pi(t - \phi) / 24) \right\|, \quad (1)$$

where *BusyLoad* is the busy hour load and *QuietLoad* is the quiet hour load, both in terms of numbers of users in the cell; ϕ is the busy hour time of day and t is the time of day, both on a 24 hour clock and in hours. Equation (1) is rounded to extend the traffic representation such that the number of users in the

TABLE I
CONFIGURATION PARAMETERS FOR NUMERICAL ASSESSMENTS

Parameter	Value
System configuration	Reflecting GSM ([4], pp. 28-30), where omnidirectional and sectorised modes each use all available resources
Operating frequency, low frequency network	900MHz
Operating frequency, high frequency network	1800MHz
Channel path loss model	Lenient path loss, reflecting, e.g., rural scenario, implying the high-frequency network requires twice the power consumption to operate (twice the number of base stations), and four times the transmission power to achieve the same received power level at a given distance
Number of channels available to the system	252
Blocking probability	1%
Number of users supported per cell in omnidirectional mode	25 ([4], pp. 28-30)
Number of users supported per cell in tri-sectorized mode	38 ([4], pp. 28-30)
Busy hour load (users per cell)	Varied
Quiet hour load (users per cell)	25% of respective busy hour load

cell might be seen as Poisson distributed, the mean of which at any one time of day is the mean cell load at that time of day. Assuming this model, the probability of there being k number of users in the cell at time of day t is expressed as

$$P(k, t) = \frac{L(t)^k e^{-L(t)}}{k!}, \quad (2)$$

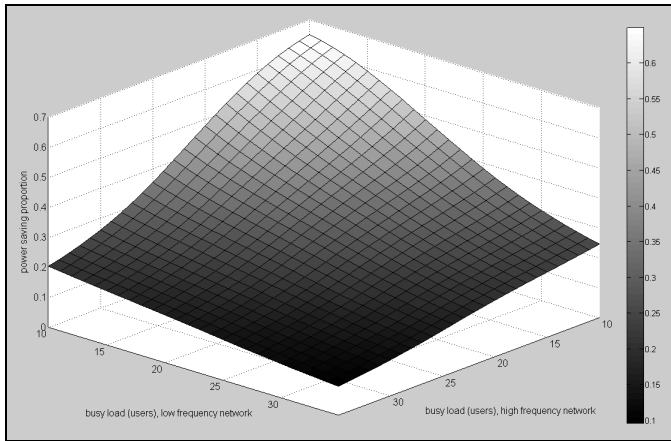
where $L(t)$ is as in (1).

We assume 252 channels available to the system and 1% blocking probability, meaning that in omnidirectional mode each cell can support 25 active users and in tri-sectorised mode each cell can support 38 active users (see [4], pp. 28-30). Note that through adaptation of such cell capacities as well as traffic characteristics, it is feasible for the concept to be applied to a range of systems aside from the chosen GSM example. Given the described traffic representation and cell capacities, our numerical assessment cycles in outer loops through a 24 hour period in steps in t of one tenth of an hour, and uses the value of $L(t)$ at each time step to parameterize (1). In inner loops, for each time step, it then cycles through each possible value of k representing each possible number of users in the cell, for each participating frequency band in the process, and for each set of k 's among the frequency bands ascertains the power consumption that would be required given the dynamic spectrum access power saving solution being applied. The actual power consumption for each such case is then given as this power consumption multiplied by the probability of it happening, which is of course the product of the probabilities of the chosen values of k occurring for the participating networks/frequencies. This result is then summed with equivalent results for all possible chosen values of k to obtain the overall power consumption at each time instance. The same

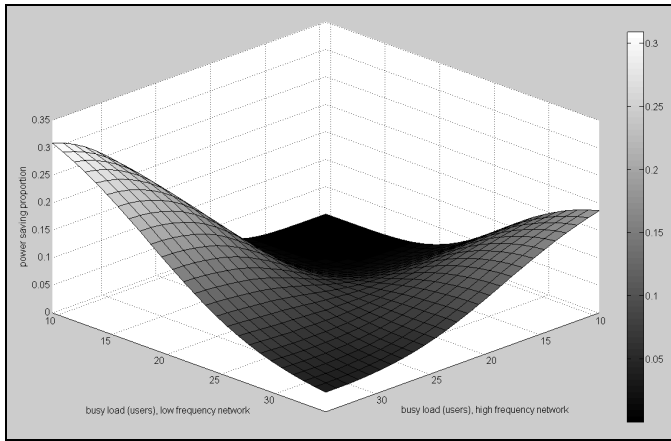
operation is performed over all time instances in the 24 hour period, and the average power consumption is then taken among all time instances. Through the same process, this average power consumption is then compared with the average

power consumption that would be required without the dynamic spectrum access power saving solution taking place.

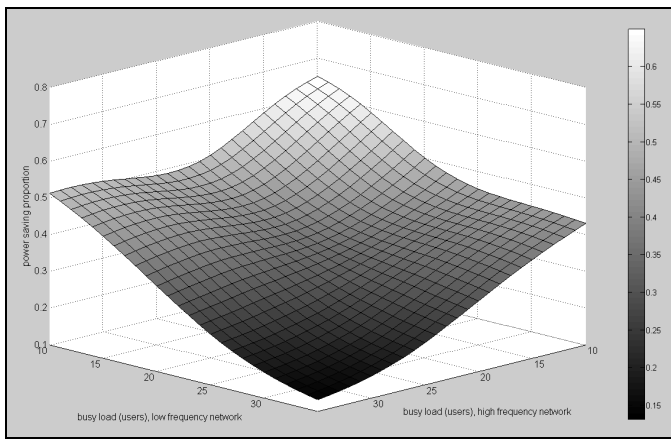
We vary the *BusyLoads* of the networks at each frequency, where *QuietLoads* are 25% of their respective *BusyLoads*. Figure 2 gives the proportion of “from-the-mains” power that is saved by applying the schemes. It is clear that very significant savings can be achieved. Most significant savings are achieved by opportunistically switching off cells at one spectrum band and allocating its users to another spectrum band. Additional significant improvements in efficiency can be achieved by the sectorization adjustment concept. The combined effect of these two concepts, for the most realistic traffic configurations (i.e., busy hour loads for the two networks being close to their capacities), is typically of the order of 30-35% power saving or more. For less common traffic configurations these savings can be far in excess of 50%. Gains through the sectorization switching solution are noticeably dominant if the high frequency network is heavily loaded and the low frequency network lightly loaded. Gains through the cell powering down solution are dominant if both networks are lightly loaded.



(a)



(b)



(c)

Figure 2. Power saving proportions achievable under the opportunistic equipment powering down concept, where the busy loads for both frequencies are varied, the quiet loads are 25% of their respective busy loads, and the high frequency network consumes twice the mains power of the low frequency network: (a) applying the network/cell powering-down solution only, (b) applying the sectorization switching solution only, and (c) applying the network/cell powering-down and sectorization switching solutions in tandem.

III. OPPORTUNISTIC REALLOCATION OF LINKS BETWEEN BANDS TO IMPROVE PROPAGATION

Under the same configuration as described in the previous section, this section investigates transmission power savings through opportunistically reallocating links to improve propagation. A more detailed description of the concept as well as results for an alternative path loss model can be obtained in [1].

Here the conservative assumption is made that the higher-frequency network requires four times the transmission power to achieve an equal reception power level at a given distance compared with the low frequency network. This is a lower bound on the difference factor between the 900MHz and 1800MHz frequencies, for a range of path loss models; in reality, the difference factor in necessary transmission power level would be a lot higher for many path loss models, particularly urban. This would greatly improve performance of the concept beyond what is presented in this section.

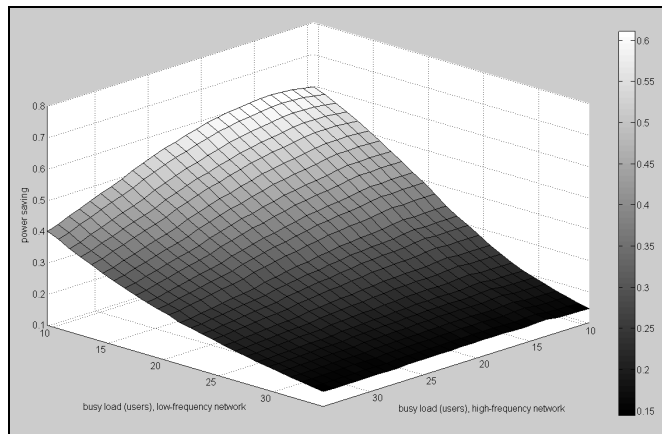


Figure 3. Transmission power savings through reallocating links among frequency bands to improve propagation.

Results in Figure 3 are for the case where there is no sectorization employed, i.e., cells are omnidirectional only. Referring to this Figure, it is apparent that there is very significant transmission power saving potential through the proposed scheme, of 50% or more in low load conditions for the network (e.g., at holiday times, for example, and particularly if the low frequency network is lightly loaded), and a lesser power saving potential of some 25-30% in more common network conditions.

IV. POWER SAVING BY BETTER INTERFERENCE MANAGEMENT

The power saving sustained through opportunistic switching off of radio equipment and opportunistic link reallocation through spectrum sharing are significant, however, this might not always be feasible as detailed in Section II. Under such circumstances, a more modest saving of power can be achieved mainly by more intelligent interference management (see, e.g., [5]). Any reduction in the received interference level can be directly translated into a reduction of necessary transmit power, which in turn can help reduce equipment's power consumption. While the effect of interference level reduction on transmit power saving is straightforward to calculate, the saving of power consumption of transmitting equipments are affected by many other parameters, not permitting a simple closed-form interrelation. Thus in this work we mainly focus on the former case and simply note that the benefits of the equipment power consumption saving, realized by dynamic interference management, are sustained over a longer time horizon compared with equipment switching-off approach described in the previous section.

Cellular operators are steadily shifting towards universal frequency reuse (UFR) as a way to enhance the capacity of the network by directly increasing the total available bandwidth per cell. On the other hand a UFR regime will result in an interference-limited capacity for the cellular network. The users located near cell-edges, specifically, will experience a lower QoS level, in terms of a lower feasible throughput and higher packet error probability in such scenarios.

A simple static solution to fix this problem is to use partial frequency reuse (PFR) which requires extensive cell planning. This solution will provide a trade-off between available bandwidth per cell and the interference level in each cell. It is, however, possible to envisage a dynamic solution based on adaptive channel allocation which can result in transmission power saving as follows. We first study a case where no specific interference limits for frequency bands are available, followed by discussion of scenarios with interference threshold requirements.

A. No Interference Limit

We assume the cellular operator has mounted dedicated transmission equipments over the same masts for the two available channels, say f_1 in 900 MHz range and f_2 in 1800 MHz. For simplicity of analysis we assume cells belonging to f_1 and f_2 frequency bands are co-located. Existing traffic load on both f_1 and f_2 bands does not satisfy condition (3) and thus it

is not possible to switch all users to one band in order to save power.

Inter-Cell Interference (ICI) is the main limiting factor on the feasible capacity of both f_1 and f_2 networks in the above scenario. Our analysis in [6] determines that for a two user scenario if the following condition holds,

$$g_{11}g_{22} < g_{12}g_{21}(2^{R_{\min,1}/w} - 1)(2^{R_{\min,2}/w} - 1), \quad (3)$$

it is not feasible to guarantee minimum QoS of users sharing that given channel, where g_{11} and g_{22} are the direct channel gains from BS1 to user 1 and BS2 to user 2, g_{12} and g_{21} are cross-channel gains between each BS and the user attached to the other BS, $R_{\min,1}$ and $R_{\min,2}$ are the minimum throughput demand for users 1 and 2, respectively, and w is the bandwidth of the shared channel.

In the aforementioned 2 user scenario, let us assume P'_1 [W] and P'_2 [W] are fixed transmission powers from BS1 and BS2. Assuming both users are scheduled over one shared channel and in order to sustain $R_{\min,1}$ and $R_{\min,2}$ for user 1 and 2, respectively, we should have

$$\begin{cases} P'_1 \geq (2^{R_{\min,1}/w} - 1) \left(\frac{P'_2 g_{21} + N_1}{g_{11}} \right), \\ P'_2 \geq (2^{R_{\min,2}/w} - 1) \left(\frac{P'_1 g_{12} + N_2}{g_{22}} \right), \end{cases} \quad (4)$$

where N_1 and N_2 are AWGN noise level for user 1 and 2, respectively. Similarly, if the two users are scheduled over two different frequency bands, the minimum power to guarantee their QoS requirements are given by

$$\begin{cases} P_1 \geq (2^{R_{\min,1}/w} - 1) \left(\frac{N_1}{g_{11}} \right), \\ P_2 \geq (2^{R_{\min,2}/w} - 1) \left(\frac{N_2}{g_{22}} \right). \end{cases} \quad (5)$$

Therefore, the power saving achieved by scheduling users over orthogonal frequency blocks, assuming transmission with the minimum required power for user 1 can be calculated as

$$\Delta P_1 = P'_1 - P_1 = (2^{R_{\min,1}/w} - 1) (2^{R_{\min,2}/w} - 1) \left(\frac{P'_1 g_{12} + N_2}{g_{22}} \right) \frac{g_{21}}{g_{11}}. \quad (6)$$

Clearly $\Delta P_1 \geq 0$, which guarantees a level of power conservation. A similar calculation steps for P_2 yields the same result as regards power saving for the second BS.

B. With Interference Limit

We have also studied the case where spectrum sharing is achieved under instantaneous or average received interference limit. In the former case, at each instant of time neighboring cells should ascertain that the ICI received at other cells are below a certain threshold. In the latter scenario, a more relaxed interference regime allows a variable level of received interference so long as the average interference over time or frequency domain remains below a certain threshold. Our

analysis shows that, surprisingly, the capacity of the primary network as well as the secondary network are higher under average interference limit due to the existence of “interference diversity gain” [7]. Conversely, assuming a fixed throughput requirement, our result dictates the possibility of transmit power conservation under an average interference limit compared with an instantaneous interference threshold.

V. THROUGHPUT IMPROVEMENT THROUGH SPECTRUM AGGREGATION WITH A MULTI-BAND SCHEDULER

Supporting additional system capacity and higher data rates through high speed Radio Access Technologies (RAT), such as the International Mobile Telecommunications – Advanced (IMT-A) [8], users can be granted universally accessible broadband services. One important enabling factor is the availability of bandwidth, which is also related to the assignment of frequency spectrum bands for IMT-A and beyond technologies [9]. This is impeded by the existing highly fragmented radio frequency spectrum that does not match the actual demand for transmission and network resources. Such fragmentation poses a challenge during dynamic spectrum use where multiple frequency bands can be assigned in support of the users and the mobile transmission system's ability to support a wide range of services across all elements of the network (i.e. core, distribution and access [10]).

The idea of this Multiband Scheduler is to explore the integration of spectrum and network resource management functionalities to the benefit of achieving higher performance and capacity gains in an IMT-A scenario. In particular, we investigate the allocation of users over two frequency bands (i.e., 2 GHz and 5 GHz) for a single operator scenario. High speed Packet Access (HSPA) was considered for the RAT for both frequency bands. It is assumed that the operator has gained access to a non-shared 2 GHz band and to part (or all) of the frequency pool band at 5 GHz.

A. Approach

The fragmented available spectrum can be virtually joined through the Spectrum Aggregation (SA) technique suggested by IMT-A and Long Term Evolution-Advanced (LTE-A) [11], [12], [13]. Information about how to aggregate contiguous and not contiguous parts of the highly fragmented spectrum to be used and how to allocate users over the dedicated and shared bands of an operator, can improve the overall system capacity.

SA can be performed in the same or in different bands and may occur when the operator's dedicated Downlink (DL) or Uplink (UL) band is not contiguous but is split into two or more parts. Enablers of SA are the advances in the area of smart antenna design, spread-spectrum technologies, software-defined radio (SDR), cooperative communications, and cognitive radio (CR) systems. Cognitive capabilities, such as sensing, access to database (in connection with geolocation), use of cognitive pilot channel (CPC), transmission power control, etc. can form a CR system capability toolbox and could facilitate coexistence/sharing in bands, where it was previously determined to be not feasible.

B. Technique

A Common Radio Resource Management (CRRM) entity with spectrum management functionalities, supported by General Multi-Band Scheduling (GMBS) was proposed in [14], [15]. By having information about how to aggregate contiguous and not contiguous parts of the spectrum to be used and how to optimally allocate users over the dedicated and shared bands, an operator can improve the overall system capacity. The optimization is based on signal quality that a MS is suffering and based on past frame receptions quality.

Depending on the capabilities at the MSs, each user may be allocated to a single frequency band or to both the frequency bands. In the latter case, the MSs have multi-radio transceivers and can transmit and receive data on both bands. Here, the focus is only on single-band MSs that need to be allocated over one of the two possible bands. Spectrum sharing mechanisms are beyond the scope of this work.

C. Results

Following the approach from [15], the performance of the algorithm is assessed by using the service throughput, i.e., the total number of bits that have been transmitted and correctly received by all users in the cell. Users are deployed in the cell with a uniform distribution within a distance of 900m with overlapping 2 GHz and 5 GHz coverage. The NRTV session generation is modeled by a Poisson distribution, and session duration is exponentially distributed with an average of 180 s.

The curves in Figure 4 enable the comparison of the results between the presence and absence of GMBS. The enhancement provided by the GMBS algorithm is clear for overloaded systems (around 55-56 users). Without GMBS, the system reaches its full capacity around 2.5 Mbps. With GMBS, it reaches the maximum capacity around 3 Mbps. A gain up to 500 kbps may thus be obtained, i.e., 20% gain. The gain is achieved by dynamically allocating resources (2 or 5 GHz bands channels) to the MS that best suits the system. The achieved improvement is relative to a scenario where users are randomly deployed on the cell.

D. Summary

This work has proposed a resource allocation mechanism for users over two frequency bands accessed by a single operator. The proposal is valuable in the scope of currently ongoing work within ITU-R towards IMT-A, and in particular the

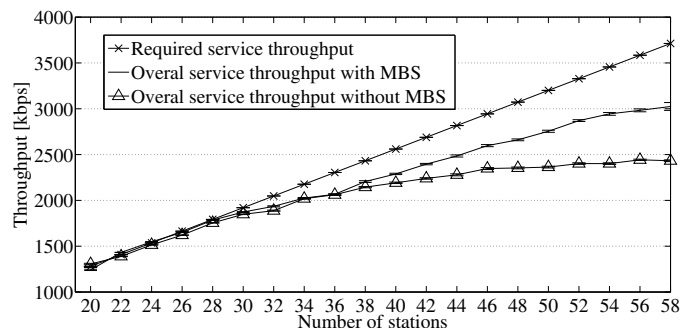


Figure 4. Service throughput with and without GMBS.

use of SA. It assumes that SA can be successfully combined with RRM techniques to optimized performance. The GMBS performance was assessed in terms of the total throughput. A gain up to 20 % was obtained with the proposed optimal solution. Future work will include the QoS requirements into the GMBS formulation via a linear combination of multiple objectives ("scalarization"). The combined solution for the packet scheduler and the spectrum scheduler is foreseen to be able to greatly reduce delay and jitters, which are of paramount importance for real time services.

VI. CONCLUSION

This paper has introduced four spectrum sharing concepts that either have the benefit of power consumption reduction or throughput enhancement. These concepts are presented in the context where a single entity (e.g., a mobile operator) owns and manages different spectrum bands and shares the usage of those bands among its systems; they might also be employable in other contexts, however, such as where the spectrum bands have different owners. It has been shown that power savings through the proposed concepts can be 50% or more, both from the mains and in terms of necessary transmission power. Throughput enhancement through the proposed spectrum aggregation scheme can be as high as 20%, especially in cases where there are a high number of users accessing the spectrum bands involved in the aggregation process.

It is intended for the concepts presented within this paper to be readily applicable to systems within the near future. Additional work on the schemes, however, is investigating their customization and parameterization across a range of systems, and aims to further quantify their benefits for a different traffic scenarios. Further work for the opportunistic radio network equipment powering down and propagation improvement concepts, for example, is looking at the application of the schemes to additional spectrum bands, and the development of a supporting network management architecture, among other areas.

ACKNOWLEDGMENT

Some of the work reported in this paper has formed part of the Green Radio Core Research Programme of the Virtual Centre of Excellence in Mobile & Personal Communications, Mobile VCE, www.mobilevce.com. This research has been funded by EPSRC and by the Industrial Companies who are Members of Mobile VCE.

The authors are thankful to Dr. Terence E. Dodgson of Roke Manor Research Ltd. for partaking in many useful discussions. The authors would also like to acknowledge the support from the following projects or grants: Marie Curie European Reintegration Grant PLANOPTI (FP7-PEOPLE-2009-RG), UBIQUIMESH (PTDC/EEA-TEL/105472/2008), and the FCT PhD grant SFRH/BD/28517/2006.

REFERENCES

- [1] O. Holland, V. Friderikos, and A. Hamid Aghvami, "Green Spectrum Management for Mobile Operators," to appear in IEEE Globecom 2010, Miami, FL, USA, December 2010
- [2] S. Thajchayapong and J. M. Peha, "Mobility Patterns in Microcellular Wireless Networks," *IEEE Transactions on Mobile Computing*, Vol. 5, No. 1, January 2006, pp. 52-63
- [3] L. Chiaraviglio, M. Mellia, and F. Neri, "Energy-aware Backbone Networks: A Case Study," Proc. International Workshop on Green Communications (GreenComm '09), Dresden, Germany, June 2009
- [4] J. Eberspächer, H.-J. Vögel, C. Bettstetter, and C. Hartmann, *GSM Architecture, Protocols, and Services (3rd Edition)*, Wiley, 2009, ISBN 978-0-470-03070-7
- [5] A. Attar, O. Holland, R. Nakhai, and A. Hamid Aghvami, "Power-Efficient Resource Allocation for Cognitive Radio in OFDM Contexts" IEEE PIMRC 2009, Tokyo, Japan, September 2009
- [6] A. Attar, M. R. Nakhai and A. H. Aghvami, "Cognitive Radio Game for Secondary Spectrum Access Problem," *IEEE Trans. on Wireless Commun.*, Vol. 8, No. 4, pp. 2121-2131, April 2009
- [7] A. Attar and V. Krishnamurthy, "Achieving Interference Diversity Gain in Frequency Domain and its Application in UMTS LTE: Capacity-Maximization and QoS-Guarantee Strategies," *IEEE Trans. On Commun.*, To appear 2010
- [8] J. Circular Letter 5/LCCE/2, *Invitation for submission of proposals for candidate radio interface technologies for the terrestrial components of the radio interface(s) for IMT-Advanced and invitation to participate in their subsequent evaluation*, ITU-R, March 2008.
- [9] Key results of World Radiocommunication Conference (WRC-07). [Online]. Available: <http://www.itu.int/dms/pub/itu-t/oth/21/04/T21040000030014PPTE.ppt>
- [10] (2008, December) EU CELTIC Project WINNER+, Deliverable 3.1, IMT-Advanced: Requirements and Evaluation Criteria. [Online]. Available: <http://projects.celtic-initiative.org/winner+/>
- [11] EU CELTIC Project WINNER+. [Online]. Available: <http://projects.celtic-initiative.org/winner+/>
- [12] FP6 IST Project WINNER and WINNER II. [Online]. Available: www.ist-winner.org
- [13] Third Generation Partnership Project 3GPP. [Online]. Available: www.3gpp.org
- [14] F. Meucci, O. Cabral, F. J. Velez, A. Mihovska, and N. R. Prasad, "Spectrum Aggregation with Multi-Band User Allocation over Two Frequency Bands," in *Proc. of IEEE Mobile WiMAX Symposium (MWS 2009)*, Napa Valley, California, USA, 2009
- [15] F. Meucci, O. Cabral, F. J. Velez, A. Mihovska, and N. R. Prasad, "Spectrum Aggregation with Optimal Multi-Band Scheduling," in *Proc. of WPMC- 13th International Symposium on Wireless Personal Multimedia Communications*, Recife, Brazil, 2010