Deployment of Indoor LTE Small Cells in TV White Spaces

A. F. Abdelkader[*], J. Pérez-Romero[*], A. Umbert[*], F. Casadevall[*], A. Kliks[+], P. Kryszkiewicz[+]

[*] Signal Theory and Communications Dept., Universitat Politècnica de Catalunya (UPC), Barcelona 08034, Spain
[+] Chair of Wireless Communications, Poznan University of Technology (PUT)
Contact email: jorperez@tsc.upc.edu

***Abstract*— This work focuses on the deployment of LTE small cells acting as secondary transmitters in TVWS for indoor scenarios making use of measurements stored in a Radio Environment Map (REM) that characterizes the DVB-T reception. Two different approaches for optimizing the positions and transmit powers of a number of small cells are presented. The first approach intends to maximize the total secondary transmit power inside the building, while the second approach maximizes the percentage of positions where the LTE receivers have a Signal to Interference and Noise Ratio (SINR) above a desired threshold. Approaches are validated by means of simulations supported by real measurements and compared against exhaustive enumeration techniques proving that they provide very accurate results. Results reveal that when considering system capacity or network throughput, the second approach is more efficient and provides better results than the first approach.**

***Index Terms*— Indoor Deployment, LTE, REM, Small Cells, TVWS**

I. Introduction

Demand for mobile broadband services has exponentially increased over the past years. This demand is a result of the social integration of wireless devices (smartphones, tablets, etc.) in our everyday life introducing applications that use an immense amount of bandwidth. This phenomena is expected to keep exponentially increasing in the near future due to new services being more and more used over the data network such as High Definition Video, 3 Dimensional Video, virtual reality, etc. Most of these services' traffic is generated indoors, which dictates a needed increase in link budget to provide higher data rates and satisfactory user experience. Therefore, a change in traditional network planning had to be made to provide these services with the high capacity they need. This change was achieved by the shift towards the so-called Heterogeneous Networks (HetNets) composed of a mix of the traditional large macro cells as well as small cells (micro cells, pico-cells, femto-cells, etc.). These small cells cover small areas such as offices, rooms, malls, etc. providing high capacity rates needed for different wireless services as well as offloading traffic from the macro cells in densely populated areas.

The use of HetNets will require efficient interference mitigation techniques in case that the small cell and the macro cell share the same band. In this respect, one option to mitigate this interference relies on the opportunistic usage of other licensed frequency bands such as TeleVision White Spaces (TVWS). Different works in literature have proven the potential and feasibility of utilizing TVWS in small cell scenarios, especially for supporting LTE services [1]-[7]. The design process of HetNets operating in the TVWS needs to ensure that the interference introduced by LTE services has to be small enough not to disrupt the (Digital Video Broadcast - Terrestrial) DVB-T services operating in the same or in adjacent channels. In [7] an analysis of the feasibility of deploying LTE small cells as secondary transmitters in TVWS in indoor scenarios was carried out based on real measurements. This study proved that, for a specific building, when operating in adjacent channels to those of the DVB-T signal, the secondary transmit power levels could be adequate for successful small cell deployment.

Starting from this previous work, in this paper we present a systematic computer-based approach to solve the problem of optimum transmitter placement and optimum transmit power determination for indoor LTE coverage systems using the TVWS, relying on the use of real measurements stored in a Radio Environmental Map (REM). In particular, this paper discusses two different approaches to the problem. The first one focuses on maximizing the total transmit power. This is done through an iterative algorithm based on a direct search optimization strategy. This algorithm is able to determine the optimum locations and transmit powers of the transmitters from a total transmit power point of view. The second approach focuses on maximizing the percentage of positions above a desired Signal to Interference and Noise Ratio (SINR) threshold, thus taking into account the mutual interference generated between small cells. The overall performance of our approach is examined through simulations.

The remainder of this paper is organized as follows. The two proposed optimization approaches will be presented in section II. The results of our simulations and experiments will be discussed in Section III. Finally, Section IV concludes this article with some conclusions and suggestions for future work.

II. Proposed Approaches

A. System Model and Assumptions

The objective of this work is to analyze different approaches that, based on the available measurements stored in a REM that characterizes the DVB-T reception inside a building, provide the optimized positions and transmit powers of a number of small cells that act as secondary transmitters. Following the previous work [7], it is assumed that the generated REM includes the following information: (i) the received DVB-T power for the different positions inside the building; this is denoted as $P_r(\theta',N)$ where $\theta'=(x,y,z)$ represents the 3D coordinates of the position (note that the different positions in the building are discretized) and N is the

DVB-T channel; (ii) the required protection ratio (PR) (i.e. the minimum signal to interference required by a DVB-T receiver) depending on the type of DVB-T receiver and the frequency separation between the DVB-T receiver and the LTE small cell [8]; this is denoted as $PR(ch)$ reflecting that the DVB-T receiver operates in channel N and the LTE small cell in channel $N+ch$; (iii) the minimum required power level $P_{r,min}$for successful DVB-T reception; (iv) an indoor propagation model to evaluate the propagation losses between points inside the building. It is assumed that DVB-T receivers can be located anywhere inside the building, as it would be when USB receivers are used.

A total of K small cell secondary transmitters are deployed inside the building operating in an adjacent channel to the one used by the primary DVB-T receivers (i.e. small cells transmit in channel N+1) and the objective is to determine the adequate positions and transmit powers of these small cells while ensuring the PR requirements of the DVB-T receivers. Then, this work presents two different techniques depending on the considered target for the optimization, namely the total transmitted power by the small cells and the percentage of positions inside the building where the LTE receivers achieve a SINR above a certain limit. In the following, the two approaches are presented.

B. *Approach 1: Maximizing Total Transmitted Power*

The first approach focuses on maximizing the total aggregated transmit power of the small cells. We would like to determine the maximum allowed power of each of K secondary transmitters located at positions $\theta_k=(x_k,y_k,z_k)$, $k=1,2,..K$, so that the aggregated interference generated onto a DVB-T receiver located at any position θ' inside the building is acceptable. Equivalently, the following condition must hold at any point θ' where a DVB-T receiver might be located:

$$\frac{P_r(\theta',N)}{\sum_{k=1}^{K}\frac{P_{Tk}(\theta_k,N+ch)}{L(\theta',\theta_k)}} \geq PR(ch) \qquad \forall\theta' \text{ s.t. } P_r(\theta',N) \geq P_{r,\min} \quad (1)$$

where $L(\theta_k,\theta')$ is the path loss between point θ_k where the secondary transmitter is located and point θ' where a DVB-T receiver might be located, and ch denotes the number of adjacent channel considered for operation (ch=1 in our study). The general multi-objective optimization problem can be then defined as follows:

$$\begin{aligned} &\arg\max_{P_{T_k},\theta_k}\left(P_{T1},\ldots,P_{TK}\right) \\ &s.t.\ \frac{P_r(\theta',N)}{\sum_{k=1}^{K}\frac{P_{Tk}(\theta_k,N+ch)}{L(\theta',\theta_k)}} \geq PR(ch) \qquad \forall\theta' \text{ s.t. } P_r(\theta',N) \geq P_{r,\min} \end{aligned} \quad (2)$$

Where we have to find the positions and transmit powers of secondary transmitters that maximize the secondary transmit power inside the building. There are many techniques to handle multi-objective optimization problems as the one we have on hand in (2). One possibility is to convert the multi-objective optimization to a single objective optimization by combining the different optimization objectives (i.e. secondary transmit powers in our case). In this respect, a viable solution is to consider the aggregate transmit power of secondary transmitters. In this case, our optimization problem becomes:

$$\begin{aligned} &\arg\max_{P_{T_k},\theta_k} P_{T1}+\ldots+P_{TK} \\ &s.t.\ \frac{P_r(\theta',N)}{\sum_{k=1}^{K}\frac{P_{Tk}(\theta_k,N+ch)}{L(\theta',\theta_k)}} \geq PR(ch) \qquad \forall\theta' \text{ s.t. } P_r(\theta',N) \geq P_{r,\min} \end{aligned} \quad (3)$$

The solution to this problem is done through an iterative algorithm based on a direct search optimization as shown in Fig. 1.

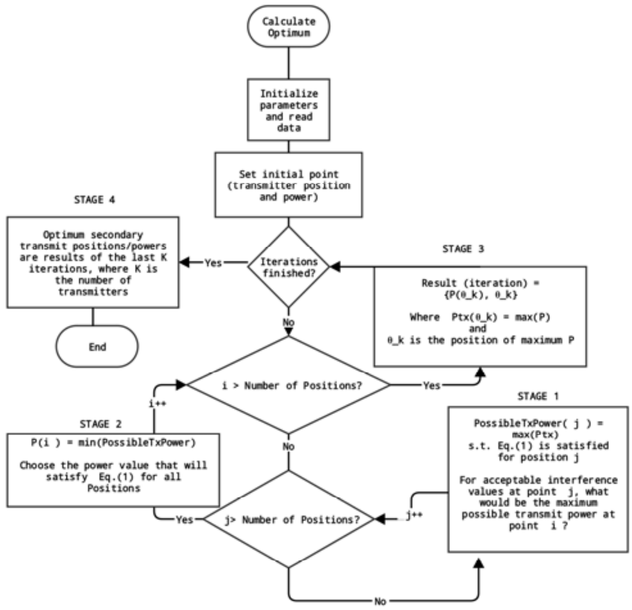

Figure 1: Flowchart of the first proposed approach. θ(x,y,z) denotes the coordinates of the possible locations inside the building while Ptx denotes the transmitted power. Index *i* accounts for the possible positions of the transmitters while index *j* accounts for the positions of the DVB-T receivers where PR constraints have to be fulfilled.

There are 2 different variables being optimized in Eq. (3), namely transmit power P_{Tk} and location θ_k. As it can be seen in Fig. 1, the algorithm includes multiple loops performing different operations. The innermost loop in stage 1 computes the maximum transmit power for a secondary transmitter placed at any of the candidate positions θ_k, which are indexed through index *i*. This is done by calculating the maximum transmit power at each possible position while still satisfying Eq. (1) at any DVB-T receiver position θ', indexed by variable j. Then, the minimum of all these possible transmitter powers is chosen in stage 2 because it is the transmit power that satisfies Eq. (1) for all positions of the DVB-T receivers. Next, the outer loop in stage 3 changes the transmitter position i, and repeats both operations in stages 1 and 2 until all candidate positions are checked. It then chooses the position with maximum secondary transmit power, and by doing that it optimizes both the position as well as the power. Finally, the algorithm does multiple iterations of the previous steps, iterating from one transmitter to another, until they all converge. After convergence, stage 4 just provides as output the result of the last K iterations as they represent the number of considered transmitters and each iteration represents the optimization process of one secondary transmitter. Then, results of these last K iterations represent optimum positions and powers of all K secondary transmitters.

It has been empirically found that performance of the solution found by the algorithm can be improved by introducing a slight perturbation in the resulting transmit power after each iteration. This avoids that the algorithm gets stuck in local optima depending on the initial starting point of the algorithm and how close it is to the global maximum. In particular, it has been obtained that a slight decrease of about 0.2 dB in the resulting transmit power of each iteration at stage 3 can ensure that the algorithm converges on a global maximum every time it operates.

C. Approach 2: Optimizing Performance Based on SINR

An increase in the number or power of secondary transmitters means an increase in Inter Cell Interference (ICI) which in turn, decreases the SINR and capacity of the network. Therefore, a second approach is suggested that intends to consider the optimization from the perspective of achieved SINR at the LTE terminals, which can be directly related to the throughput and capacity. Then, the optimization problem tries to maximize a Quality Indicator (QI) representing the percentage of positions in the building above a desired SINR threshold. Our new optimization problem is then:

$$\begin{aligned} &\arg\max_{P_{Tk},\theta_k} QI \\ &s.t.\ \frac{P_r(\theta',N)}{\sum_{k=1}^{K}\frac{P_{Tk}(\theta_k,N+ch)}{L(\theta',\theta_k)}} \ge PR(ch) \qquad \forall\theta' \text{ s.t. } P_r(\theta',N) \ge P_{r,\min} \end{aligned} \tag{4}$$

where QI is the percentage of positions θ' where the following condition holds:

$$\frac{\frac{P_{Tn}(\theta_n,N+ch)}{L(\theta',\theta_n)}}{P_{Noise}+\sum_{\substack{k=1\\k\neq n}}^{K}\frac{P_{Tk}(\theta_k,N+ch)}{L(\theta',\theta_k)}} \ge SINR_{th} \tag{5}$$

Where transmitter *n* corresponds to the transmitter providing coverage to position θ' (i.e. the transmitter with highest received power at that position), $SINR_{th}$ is the desired SINR based on modulation and coding requirements, and P_{Noise} is the noise power measured in the channel. It is worth mentioning that (5) does not consider the interference generated by DVB-T transmitters operating in channel *N* to the LTE receivers operating in channel *N*+*ch*. The reason is that the practical measurements carried out in the building have revealed that this interference can be neglected in comparison with the noise power and the interference coming from the other co-channel small cells.

The solution to the optimization problem of Eq. (4) has been obtained by means of an exhaustive enumeration method that looks through all the candidate positions and transmitted power levels.

III. PERFORMANCE EVALUATION

This section presents the evaluation of the two approaches discussed in Section II. To that end, several simulations have been executed to test our algorithms in many aspects such as accuracy, time consumption and SINR.

A. Scenario Description and Parameters

We consider as a reference for the evaluation the measurements of the DVB-T signals collected in [7][10] for a building of the department of Signal Theory and Communications (D4) in Universitat Politècnica de Catalunya · BarcelonaTech (UPC) Campus Nord (latitude: 41° 23' 20" N; longitude: 2° 6' 43" E; altitude: 175 m). The building consists of 3 floors and 1 basement floor. Measurements used in this paper correspond to channel *N*=61 (794 MHz). The discrete set of measured positions includes a total of 83 points distributed within the entire building. We assume that DVB-T receivers can be located at any of these points via portable USB receivers connected to laptops. Similarly, these points are also the candidate positions for the small cell transmitters. However, it is worth mentioning that the same methodologies can be applied if more measured points existed in the building or if interpolation of current available measurements was used to define more measurement points, but this is left for future work.

One more thing that has to be taken into consideration is that results obtained in [7] revealed that in the considered building small cell deployment using co-channel transmission is not feasible due to the very low resulting allowed transmit power. Therefore, we limit our investigation in this paper to adjacent channel transmission (i.e. *ch*=1), which was found more adequate for successful small cells deployment. For the scope of this work we take as a reference a fixed PR value of -31 dB. This value was determined based on extensive measurements done in [11] for different types of DVB-T receivers and LTE transmitters while assuming LTE transmission in the first adjacent channel.

The noise power at the LTE receivers is P_{Noise} = -98 dBm, corresponding to a bandwidth B=8 MHz and a 7 dB noise figure. In addition, as previously discussed, the results of Approach 2 do not consider the interference generated by DVB-T transmitters operating in the adjacent channel to a small cell receiver. In this respect, the measurements have revealed that this interference is in the range of -100 dBm to -120 dBm, which is lower than the noise power and the ICI from other small cells (which our simulations show that it ranges between -80 dBm and -100 dBm). Therefore, the assumption of neglecting the interference exerted from DVB-T transmitters on LTE receivers is considered to be valid in this study.

B. Evaluation of Approach 1

Figs. 2 to 5 shows graphically the optimum locations and associated transmitted power levels for the cases of *K*=2, 3, 4 and 5 transmitters. We observe that the locations of transmitters found by the algorithm are in general clustered in one area that corresponds to the first floor and northern side of the building. This observation is explainable if we consider that this area includes the positions of the building with the highest DVB-T received signal strengths. Then, in order to provide higher secondary transmit power, the algorithm must place the transmitters in positions with higher DVB-T received signal strength, so that the PR constraints can be more easily fulfilled.

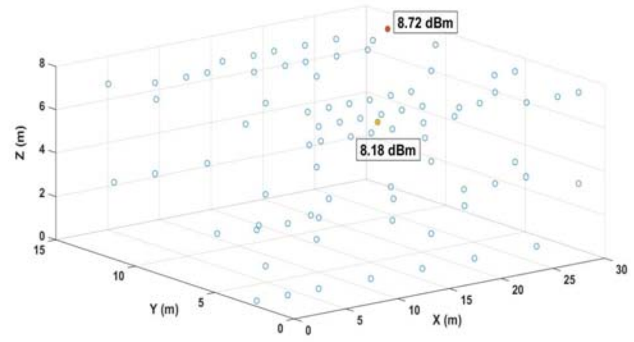

Figure 2: Location of optimum secondary transmitters and transmitted power levels with *K*=2 transmitters

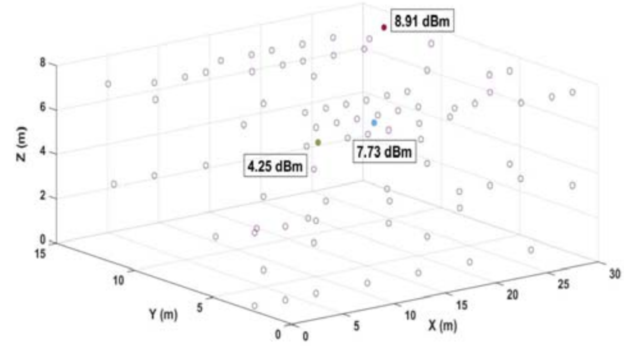

Figure 3: Location of optimum secondary transmitters and transmitted power levels with *K*= 3 transmitters

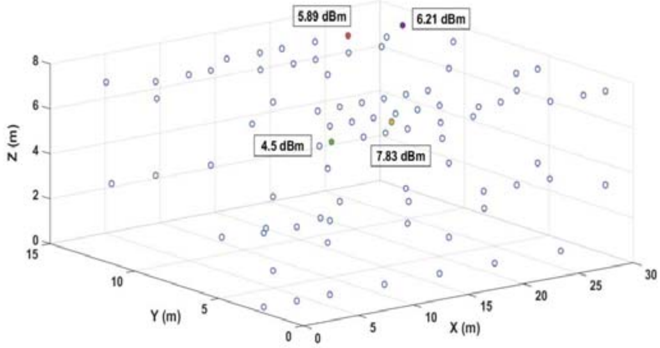

Figure 4: Location of optimum secondary transmitters and transmitted power levels with *K*=4 transmitters

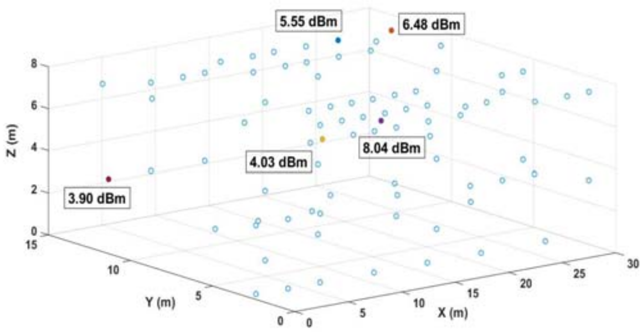

Figure 5: Location of optimum secondary transmitters and transmitted power levels with *K*= 5 transmitters

In order to investigate the efficiency from a SINR point of view, Fig. 6 plots the total aggregated transmit power and the average downlink SINR of the LTE receivers inside the building against the increasing number of secondary transmitters *K*. As it can be seen, increasing the number of transmitters causes an increase in total transmit power. This, in turn, causes an increase in inter-cell interference and results in a drop in the average SINR (defined as the averaging of measured SINR between all measurement points). The actual value of the SINR depends on the positions that are selected by the algorithm for each transmitter, which in turn depend on the number of transmitters. Then, for up to *K*=4 transmitters, the algorithm tends to locate them in relatively close positions (as seen in Figs. 2 to 4), so SINR decreases, while for *K*=5 one of them is located a distant part of the building (see Fig. 5), so that a slight increase in SINR is achieved with respect to *K*=4.

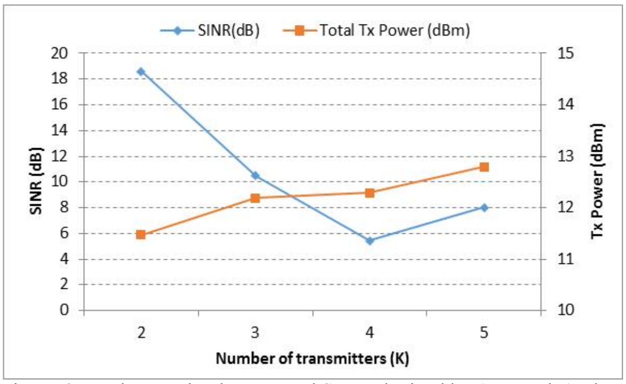

Figure 6: Total transmitted power and SINR obtained by Approach 1 when increasing the number of transmitters *K*.

When comparing our approach to brute force method, also known as exhaustive enumeration, which looks for all the possible power values according to a certain resolution (0.5 dB in this case), the optimum transmit power values provided by our algorithm are proven to be very accurate as shown in Table I. In addition, the computation time of the proposed approach is significantly reduced to 1.2 seconds, while the exhaustive enumeration method can last for 82 seconds in the case of *K*=2 transmitters and this duration increases exponentially with each secondary transmitter added.

Table I: Comparison between the results obtained with approach 1 and with the exhaustive enumeration method with 0.5 dB resolution.

	Brute force algorithm	Proposed algorithm
Transmitter 1	8 dBm	8.18 dBm
Transmitter 2	8.5 dBm	8.73 dBm
Total transmit power	11.27 dBm	11.47 dBm

C. *Evaluation of Approach 2*

In order to examine the validity of the approach, different simulations were done for different modulation schemes and SINR thresholds based on [9]. We present some illustrative results in Table II. Fig.7 depicts the positions of the transmitters for one of the considered cases.

Table II: Results of Approach 2 with K=2 transmitters and different modulation schemes.

Modulation Scheme	Min SINR required	Tx 1 power	Tx 2 power	QI (%)
16 QAM - 2/3	11.3 dB	7.5 dBm	7 dBm	98.79
16 QAM - 3/4	12.2 dB	7.5 dBm	7 dBm	98.79
64 QAM - 2/3	15.3 dB	7.5 dBm	7 dBm	95.18
64 QAM - 3/4	17.5 dB	2 dBm	0 dBm	78.31

From the results presented, it can be seen that the same transmit powers are obtained for the first three modulation schemes in Table II, while the case of 64 QAM-3/4 results in a reduction of transmit powers. The positions of the transmitter for this case are shown in Fig. 7, where it is observed that the transmitters are located in different sides and floors of the building. This constitutes a difference between the operation of Approach 1 and Approach 2: while Approach 1 tends to clustering the transmitters in the same side of the building (see Fig. 2), Approach 2 distributes the transmitters to improve the SINR conditions. As it can be seen in Table II, Approach 2 is able to achieve quite high values of the percentage of positions above $SINR_{th}$, up to 98%. It is important to note here that this algorithm optimizes only 2 different variables so far, transmitter locations and transmit powers. However, it can be extended to consider also the number of transmitters.

It is also worth mentioning that, while the approaches are only tested in the considered building where measurements have been obtained, the methods used are generic and can be applied in the same manner within other environments provided that the REM for that environment is established.

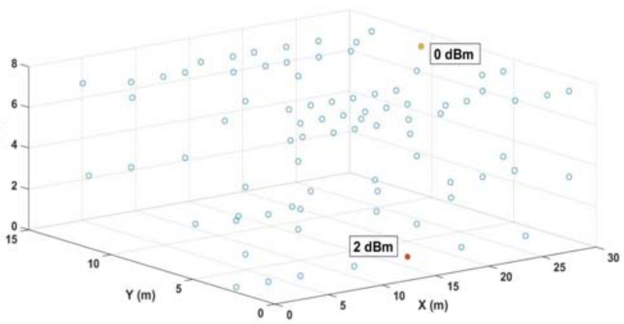

Figure 7: Optimum positions of 2 secondary transmitters in the case of min SINR required by 64 QAM-3/4 Modulation scheme

IV. CONCLUSIONS

This article has proposed two different approaches to deploy indoor LTE secondary transmitters in the TVWS band assuming adjacent channel transmission. The objective was to introduce a model capable of optimizing secondary transmit powers and locations of secondary transmitters for a given scenario.

First, an approach was proposed based on maximizing the total secondary transmit power. Results have shown that maximizing the total secondary transmit power in some cases degrades the average SINR, hence the capacity of the system, particularly when increasing the number of secondary transmitters. Therefore, another approach was introduced based on maximizing the percentage of positions with SINR values higher than a desired SINR threshold.

The performance of both approaches has been studied by means of simulations that make use of real measurements obtained in a building. The performance in terms of accuracy, time consumption and SINR has been obtained for different numbers of transmitters. Despite having not considered optimizing the number of transmitters in our approaches, the authors believe that the two approaches can be extended to include also this optimization.

Future research derived from this work can focus on different points. First, the optimization algorithm for Approach 2 can be enhanced for the sake of time efficiency, since for the time being just an exhaustive search was used. Second, the performance evaluation could also include the effect of external buildings and of interpolated versions of the REM, which extend the number of points by mathematically interpolating the available real measurements.

ACKNOWLEDGEMENT

This work has been supported by FP7 NEWCOM# project (grant number 318306) and by the Spanish Research Council and FEDER funds under RAMSES grant (ref. TEC2013-41698-R).

REFERENCES

[1] J. Xiao, R. Q. Hu, Y. Qian, L. Gong, B. Wang "Expanding LTE Network Spectrum with Cognitive Radios: From Concept to Implementation", IEEE Wireless Comms, April, 2013, pp. 13-19

[2] J. Zander, L.K. Rasmussen, K.W. Song, P. Mähönen, M. Petrova, R. Jäntti, J. Kronander, "On the scalability of Cognitive Radio: Assessing the Commercial Viability of Secondary Spectrum Access", , IEEE Wireless Communications, April, 2013, pp.28-35

[3] T. Dudda, T. Irnich, "Capacity of cellular networks deployed in TV White Space", IEEE International Symposium on Dynamic Spectrum Access Networks, 2012.

[4] A. Achtzehn, M. Petrova, P. Mähönen, "On the Performance of Cellular Network Deployments in TV Whitespaces", IEEE ICC 2012.

[5] C. F. Silva, H. Alices, and A. Gomes, "Extension of LTE operational mode over TV white spaces," Proc. of Future Network and Mobile Summit, 2011. .

[6] J. Markendahl, P. Gonzalez-Sanchez, and B. Molleryd, "Impact of deployment costs and spectrum prices on the business viability of mobile broadband using TV white space," Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2012 7th International ICST Conference on, pp. 124–128, June 2012.

[7] A. Umbert, J. Perez-Romero, F. Casadevall, A. Kliks, and P. Kryszkiewicz, "On the use of indoor Radio Environment Maps for HetNets deployment," Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), 2014, 9th International Conference on, pp. 448–453, 2014.

[8] H. Aiache, "Use-cases Analysis and TVWS Systems Requirements," Deliverable D3.1 of the COGEU project, August 2010.

[9] Rhode and Schwarz, "LTE: System specifications and their impact on RF and Base-Band circuits," Application Notes.

[10] A. Kliks, P. Kryszkiewicz, A. Umbert, J. Perez-Romero, and F. Casadevall, "TVWS Indoor measurements for HetNets," Wireless Communications and Net-working Conference Workshops (WCNC), 2014 IEEE, pp. 76–81, 2014.

[11] G. Stuber, S. Almalfouh, and D. Sale, "Interference analysis of tv-band whitespace," Proceedings of the IEEE, vol. 97, pp. 741–754, April 2009.