Evaluation of Spectrum Access Options for Indoor Mobile Network Deployment

Ashraf Awadelkarim Widaa Ahmed, Jan Markendahl and Amirhossein Ghanbari
Wireless@KTH, KTH Royal Institute of Technology
Stockholm, Sweden
Email: {ahmed2, janmar and amigha} @kth.se

Abstract— **The investment in indoor mobile market is highly related to the spectrum availability and its associated authorization options. The aim of this paper is to discuss the differences in the spectrum demand considering both wide and local area network deployment and what kind of actor that provides the indoor wireless access service. The analysis includes licensed, unlicensed, licensed shared access and secondary access of spectrum. A quantitative approach is used to analyze the differences between macrocell and femtocell deployment focusing on deployment cost and spectrum demands. This is complemented by a qualitative study to explore and discuss the strategic business decision of different actors concerning the available spectrum bands and spectrum access options.**

The main conclusions from this study are; the spectrums have more value in macrocell deployment scenarios compared femtocell case. More spectrum in macrocell deployment scenarios means that operators can deploy less number of new sites and exploit previous infrastructure investments. Femtocell networks are often coverage limited and the frequencies can be re-used. Hence, the value of spectrum is different for mobile network operators (MNOs) and local network operator (LNOs). MNOs are traditionally locked to macrocell deployment strategies and this requires exclusive usage of licensed bands. In contrast, in LNO case the licensed spectrum prices may cost more than the infrastructure cost. That is why unlicensed bands are more feasible for LNO. However in view of the technical and regulation development, the LSA could soon become enabler for LNO`s business.

Keywords— Business models, Cost and capacity analysis, Licensed and unlicensed specttrum, Outdoor and indoor network deployment, Mobile broadband, Spectrum access.

I. INTRODUCTION

The demand for mobile broadband access has increased dramatically in present days in term of the connections number and traffic volume. Starting from year 2010 around 80% of the generated data traffic comes from indoor environment [1]. Thus, mobile operators are looking to find optimum ways to provide the required network capacity in places where it's really needed such the crowded business districts. In last few years, Wi-Fi networks are utilized by mobile operators to offload their data traffic, which normally required agreements with the facilities owners. Studies on Wi-Fi networks discuss the possible negative impact on the network capacity as a result of the network densification due the lack of good interference coordination mechanism [2]. Nowadays, the use of indoor small cells (i.e. femtocell) gets more attention as a cost efficient solution to provide the coverage and capacity requirements in indoor locations. However, if the same macrocells frequency band is used for femtocell deployment co-existence and interference problems may arise. In addition to that, mobile network operators are usually not willing to allocate part of their licensed spectrum for dedicated femtocell deployment.

Hence, there is an interest for femtocell deployment to look into alternative spectrum bands and access solutions like unlicensed, licensed shared access or dedicated licensed bands using local licenses. Beside the technical aspects there are also economic and regulatory issues to consider. The spectrum cost and availability is an important issue for the mobile wireless network in general.

When it comes to femtocell deployment, the national regulator authorities (NRAs) are used to treat the femtocell similar to any other base stations. However a new trend is taken place now. As an example, Ofcom, the UK communications regulator, is discussing the possibility of allocating portion of the 2.6-GHz band for exclusive femtocell deployment [1]; another opportunity may arise for femtocell deployment in part of the 1800 MHz band, traditionally allocated to the DECTS system, that become an unlicensed band in Europe and USA [3] [4]. Further on, in Sweden 5 MHz in 1.8 GHz (IMT band) will become unlicensed by early 2014, as depicted in Fig.1. There are differences between outdoor and indoor network deployment. For indoor deployment with femtocell high bandwidth is not the key issue, it is more essential to have access to "some" spectrum and to be able to control it within a building or local area. Business model aspects also need to be considered [5] since the indoor access can be provided by one or several mobile operators or by an independent local operator offering capacity or local roaming services.

The aim of this paper is to analyze the spectrum needs and the spectrum access options of interest for indoor mobile broadband deployment. Related to this, the economic value of different spectrum bands for different types of actors are analyzed. The research questions are:

1. What are the main differences in spectrum needs for outdoor and indoor deployment?
2. What is the value of the spectrum for mobile operators and for local network operators?

The paper is organized as follows; related work and the research approach are described in sections II and III respectively. Different spectrum access options are introduced in section V. The results from the quantitative and qualitative studies are presented in sections V and VI. Section VII summarizes the paper.

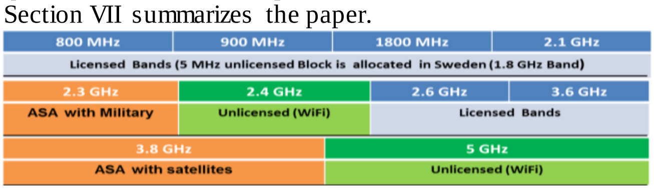

Fig 1 Spectrum Bands With Different Types of Access Rights

II. RELATED WORK

A. Spectrum Accces Options

Discussing spectrum allocation and different types of spectrum access solutions is influenced by the growing mobile broad band traffic for different types of research. This leads the research towards evaluating the need for and the benefits of additional spectrum [6]. Different alternatives to allocation of more licensed spectrum are currently discussed, examples are secondary spectrum access, licensed/authorized shared access (LSA/ASA) [7] [8] [9]. As Zander et al [10] points out, secondary access and LSA and ASA concepts are interesting for indoor deployment due to low power levels and protection by wall penetration losses.

B. Spectrum Access Options for Indoor Deployment

Spectrum sharing between macrocells and femtocells and its related benefits and problems are discussed in [11]. This continues by discussing portioned spectrum usage to deploy femtocells in the context of the LTE networks [12]. In [13] an economic framework is derived to compare the economic viability of two spectrum schemes; split spectrum and common spectrum for the femtocells deployment in a 4G network. In [14] the authors built a simple decision model to examine the choices that a potential secondary spectrum entrant may take consider cost and revenue components. As an alternative solution to share frequency between macro/femtocells, discussions regarding possible deployment strategies combining femtocells and cognitive elements (cognitive sharing for licensed spectrum) are presented in [15] [16] [17] where its promotion by proper regulations and standardization is presented in [18]. Cognitive femtocells mainly aim to overcome spectrum scarcity [19] as well as causing coverage holes in macrocells [17] along with certain drawbacks and advantages [20].

C. Spectrum Valuation

The area of valuation of spectrum generates interest for industry, operators, consultants, academia, regulators and governments. In [21], Plum presents a review of the value of spectrum licenses, model values based on expected revenues and costs for a hypothetical operator. The Australian government [22] applies an opportunity cost modeling, which it defines as the highest value alternative forgone, but underscores that the opportunity cost pricing differs according to circumstances. Doyle [23] states that it is necessary to take account of the opportunity cost values associated with alternative uses and across different frequency bands used by different users. An engineering value of spectrum is estimated by calculating the cost savings facilitated by additional spectrum bands compared to building out existing networks that provide the same capacity as the network with additional spectrum. Yeo [24] estimates spectrum values based on calculations from auction data and with an analysis of observed bidding behavior through an econometric model. ITU [25] presents an approach to valuation of spectrum in order to facilitate for spectrum regulators to determine reasonable expectations on market-based revenues for the spectrum in beauty contest or administrative distribution processes, and for spectrum auctions to determine reserve prices.

The contribution in this paper is to identify and analyze the key aspects of spectrum value for indoor deployment and to highlight the differences compared to outdoor deployment

III. METHODOLOGY

A dual quantitative and qualitative research approach is adopted in this study. The quantitative study discusses the differences between macrocell and femtocell deployments focusing on deployment cost and spectrum demands. In addition to that, qualitative approach is used to add more discussion regarding the perspectives of different actors (i.e. Local Network Operators (LNOs) and Mobile Network Operators (MNOs)) concerning the available spectrum options and their associated investment decision. In this regard, representatives from industry and regulatory authority have been interviewed between year 2010 and 2012 in order to understand the trends in indoor deployment.

A. Users Demand

In this study the deployment of a mobile network infrastructure to meet the expected subscribers demand in a new crowded business district within an area of one square kilometers has been considered. Ten thousand mobile subscribers are assumed to be existed in the new business district. Those subscribers are assumed to be uniformly distributed in ten (10) five floors buildings. Two levels of the mobile subscriber`s demand per month are assumed; i.e. 5 GB and 20 GB for low and high demand respectively. Assuming 8 busy hours per day, an average data rate per mobile subscriber of 50 and 200 Kbps can be estimated in low and high demand levels respectively. For the macrocell solution we assume three sector sites and an average cell spectral efficiency of 1,7 bits per second per Hz. While in femtocell solution one sector and average spectral efficiency of 2 -4 bps per Hz are assumed.

B. Cost Structure

The total investment cost inquired by operators to satisfy the indoor users demands as previously described, includes the radio site build-out cost (i.e. civil work, radio equipment and backhaul solution, auxiliary systems etc.) in addition to the spectrum license fee.

In Sweden, The cost of deploying one macrocell ranges from k€ 50 to k€ 200, for the purpose of this study cost of deploying new macrocell site is estimated to be around k€ 100. While in the femtocell deployment scenario, k€ 1 is estimated as deployment cost per base station. Around two to four femtocell base stations per floor, depending on the minimum allowed data rate at cell edge (i.e. SNR value), are estimated to be required in order to provide the required coverage and capacity level.

IV. TAXONOMY OF SPECTRUM ACCESS

The spectrum resources are essential means to rollout and deliver the mobile communication services. The challenge is how to manage and utilize this resource in most efficient way to satisfy the increasing demand. Nowadays, there are two main ways for allocating and authorizing the use the radio spectrum bands; namely the Individual Authorization and General Authorization, as shown in Fig.2. In each of these two authorization options, two usage levels are distinguished, namely primary and secondary usage. Those usage cases (primary and secondary allocation) appear in the ITU´s Radio Regulations to give clear prioritization if several radio services could use the same frequency band. In the following, the different spectrum access/sharing models with their corresponding use cases and different authorizations options are presented [26] [27].

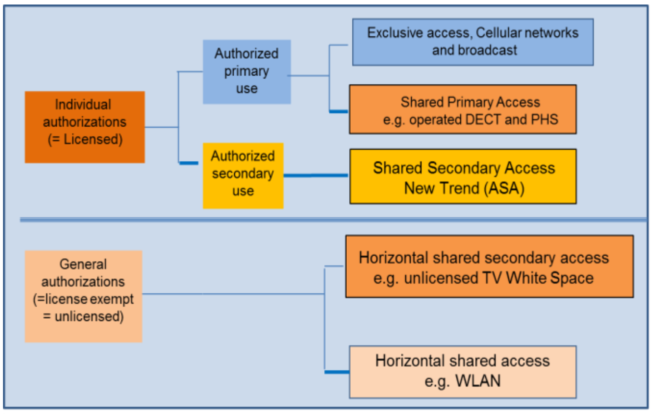

Fig 2: Spectrum Authorization Option

A. *Individual Authorization*

In the individual authorization, the right to use a specific spectrum band is exclusively granted by the National Regulatory Authority (NRA), to specific actor for certain period of time and with specific geographic region. As shown in Fig.2, different levels of spectrum access could exist in individual authorization; namely authorized primary use and authorized secondary use as shown in Fig.2. Within the authorized primary license, the actor (licensee) will have an exclusive access right to use the assigned spectrum and any other secondary user couldn't claim protection or cause harmful interference to the service offered by the licensee. However, sometimes the licensee will have an equal access rights without priorities, i.e. shared primary access, to the frequency band with other primary license holders. While in the authorized secondary use, a primary license holder (incumbent) could grant spectrum access rights to one or more other users under specific terms and conditions (known as shared secondary access). As shown in Fig.1, a good example can be given by the emerging LSA/ASA.

B. *General Authorization (Unlicensed or License exempt)*

In the general authorization, the access right to use the spectrum is granted without license fee to all actors if certain technical and regulation conditions are met. These unlicensed bands are shared between different systems without any guarantee of any sort of interference protection which may affect the QoS. As illustrated in Fig.2, two types of General Authorization could be distinguished; namely unlicensed shared access (also known as Horizontal Shared Access) and the secondary horizontal shared access. In the Horizontal shared Access, users share the band horizontally without protection rights against each other (the most common example is the ISM band at 2.4 GHz). While in the Secondary Horizontal Shared Access, there is a condition to protect the service of users with higher priority (primary users). The secondary access in the VHF/UHF TV band, often referred to as TV white space (TVWS), could be considered as good example of the Secondary Horizontal Shared Access.

V. SPECTRUM VALUE: INDOOR VS. OUTDOOR DEPLOYMENT

In case of outdoor deployment (wide area coverage), the use of low frequency bands are of interest due to good propagation properties like long range and lower wall penetration losses. Wide bandwidth is beneficial in order to provide high data rates and capacity but also from a cost perspective. More system bandwidth means less number of base stations to satisfy a given demand.

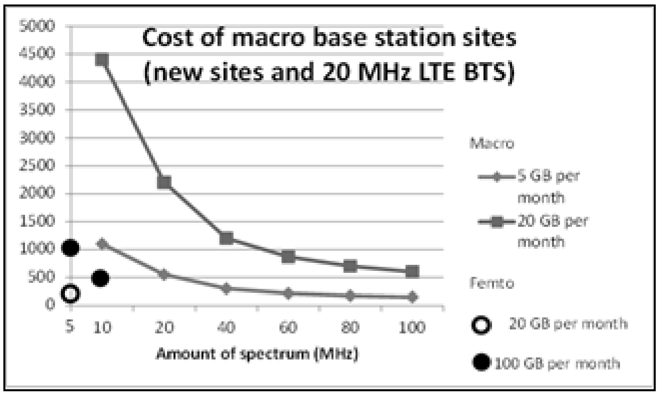

Fig 3: Deployment Cost (Macrocell vs. Femtocell)

Recalling the described scenario and assumption in section III, the infrastructure cost is given by Eq. (1) [28], where $A_{service}$ is the size of the service area, W_{sys} is the available (spectrum) bandwidth, η is the effective reuse factor, R_{user} is the average guaranteed data rate per user, N_{BS} represents the number of base stations and C_{BS} is cost per base station.

$$C_{infra} \approx C_{BS} N_{BS} = C_{BS} c_A \frac{N_{user} R_{user} A_{service}}{\eta W_{sys}} \quad \textbf{(1)}$$

With this model we can estimate the number of sites required satisfying the user demand with different amounts of bandwidth.

As shown in Fig. 3, the value of spectrum is clear in macrocell deployment, with more bandwidth the same capacity can be provided with less number of sites, or higher capacity can be provided with a given number of sites. In Sweden the mobile operators have spectrum in the 800, 900, 1800, 2100 and 2600 MHz bands. In the three upper bands the operators have up to 60 MHz, i.e. with network sharing and spectrum pooling cooperating operators can have well above 100 MHz. The benefit compared to operators with less amount of bandwidth is evident from Fig 3. For macrocell deployment licensed shared access (LSA) is of interest since it gives the operator exclusive usage rights. The LSA spectrum can be added to the licensed spectrum and the operator will move to the right in Fig 3. Other types of spectrum access are of less interest for macrocell deployment since other users may co-exist. The value of additional spectrum can be estimated by the additional costs that would result if the additional spectrum was not acquired. Analysis using this so called engineering value is presented by many researchers [21] [22] [23]. In many cases the engineering value show large variations due the made assumptions, also the relation to auction prices can vary a lot [29] [30].

For indoor deployment the situation is different both when it comes to the frequency bands of interest and the potential business cases (see section VI). Indoor wireless access means short range communication and a positive impact of wall penetration losses since the interference from neighbour cells is reduced. Hence, higher frequency bands with shorter range are of interest. In the femtocell case, the capacity is provided by many base stations that anyway are required in order to provide the indoor coverage. In the femtocell case more spectrum does not result in cost savings, just overprovisioning of capacity. In order to explain this further, a capacity-demand analysis has been conducted as illustrated in Table I, assuming 200 users per floor and 4 femtocells are required to provide the necessary coverage.

TABLE 1 SPECTRUM VS. CAPACITY DEMAND (FEMTOCELL DEPLOYMENT)

System bandwidth (*MHz*)	Spectral efficiency (*bps / Hz*)	System Capacity (*Mbps*)	No served 10GB users	No served 50GB users
5	10	50	500	100
5	1.0	5	50	10
20	10	200	2000	400
20	1.0	20	200	40

Let us assume that the indoor users consume 10 GB per month today and will consume 50GB in the "future", the number of users that can be served in both cases has been estimated as shown in Table I. The data is consumed during 8 hours of the day (all equally busy) during 30 days. This corresponds roughly to average bit rates 0.1 and 0.5 Mbps, note that this is average number used for capacity estimates. We consider femtocell using 5 or 20 MHz of spectrum. In order to do a sensitivity analysis in the dimensions demand, allocated spectrum and deployment strategies we also vary the spectral efficiency and use the values 1 and 10 bps per Hz. This can be compared to the 3GPP and ITU target values of 15-30 for the peak values and around 2 for the cell averages.

VI. ACTORS AND THE SPECTRUM ACCCESS OPTIONS

Many actors, e.g. MNOs, LNOs and facility owners can build and operate indoor wireless networks. Different levels of cooperation and business settings can be identified when it comes to the ownership and operation of indoor networks. Aspects like business model, complexity, interoperability with outdoor cellular systems, QoS, cost and regulation environment are used to discuss the actor decision concerning the spectrum options.

A. Indoor Network Deployed and Operated by a MNO

MNOs tend to be in favor of macrocell deployment strategies in which a stable and guaranteed access to spectrum resources is a key requirement for providing good QoS and sustaining competitive advantage in the market. Access to low frequency bands and wide spectrum bandwidth play a key role in reducing the deployment cost. Adding more spectrums will lead to overall reduction cost as far as the spectrum price remains small compared to the network infrastructure cost, a condition can be challenging for indoor deployment. That is why MNOs tend to be unwilling to use dedicated licensed bands for indoor deployment, even if better QoS can be achieved. Moreover, deploying an indoor mobile network brings extra activities and overhead to MNOs. Establishing relations with a number of facility owners may not be within the scope of the MNO core business. Alternative solution such as outsourcing and offloading MNO's data traffic from its wide area networks to wireless local area networks become attractive approaches. However, the mobile subscribers cannot seamlessly move between Wi-Fi and outdoor cellular sites. Recent advances in WiFi standards and new trends to manufacture and deploy an integrated Femto-WiFi (IFW) access point may bring such problem to an end. Even though, the IFW still need to use the licensed band of MNOs.

As shown in Table.2, the use of secondary access, unlicensed bands or LSA could be considered as additions to the existing licensed bands of MNO`s which means more flexibility to expand their indoor network. The advantage of using dedicated frequency bands in indoor locations would be that operators will avoid interference problems and at the same time can use all "own" spectrum for macro base stations.

B. Indoor Network Deployed and Operated by a LNO

The LNOs business model focuses on providing the indoor mobile broadband services in local indoor locations with high subscribers demand such as office buildings and shopping malls. The drivers for dedicated indoor system can be problems with wall penetration losses using outdoor base stations or that the users in the building want dedicated and ensured capacity. In this regard, the first business model for a LNO is to act on behalf of MNOs, negotiating with other actors such as facility owners in order to build and operate the indoor mobile network. In this case the LNO could utilize the available spectrum resources of the MNOs to rollout the indoor mobile network. In order to achieve better QoS in indoor network, a dedicated spectrum from MNO`s license bands can be allocate to the LNO depending on the spectrum availability.

The second business option for LNOs is to build independent indoor mobile networks. In this case, the LNO will act as third party in the market and could enter into different level of cooperation and partnership with different actors in the market such as MNOs. Now the spectrum availability (LNO with no licensed bands) becomes an issue for LNO to secure its business investment and to expand its network in terms of coverage and capacity. For LNO, spectrum resources could be secured via different spectrum access options as shown in Table.2: the first option is to use more licensed spectrum which is costly and hard to secure.

The second option is to use more unlicensed bands enabled by recent allocation in IMT/IMT-advanced (e.g. 5 MHz allocated in 1.8 Hz as shown in Fig.1). This option is cost-effective and enables seamless operation and interoperability with the existing cellular systems (i.e. voice service) when compared to the use of WiFi. The third option is to exploit frequency bands allocated for another no communication systems in secondary access base (e.g. Broadcasting (TVWS) and aeronautical bands as shown in Fig.1). Key obstacles for cognitive radio and secondary spectrum access solution are the availability and cost of network and end-user equipment. In this regard, the use LSA approach could provide long term and stable conditions that may bring manufacture support to invest in user and network equipment.

TABLE 2: ACTORS' BUSINESS SETTINGS VS. SPECTRUM OPTIONS

	Business Settings		
Spectrum Options	**MNO**	**Independent LNO**	**LNO acting on behalf of MNO**
Dedicated Licensed Band<6GHz	(-) Spectrum cost and availability	(-)Spectrum. Cost.- (-)Regulation (-)Availability	(-) Spectrum cost. (-)Availability
Licensed shared Access	(-/+) cost. (-) regulation (-/+) Interoperability	(-/+) cost. (-) regulation (-/+) Interoperability	(-/+) cost. (-) regulation (-/+) Interoperability
Unlicensed – WiFi-	(-) QoS (-) Interoperability	(-/+) QoS (-) Interoperability	(-/+) QoS (-) Interoperability
Unlicensed bands -IMT-	(-) regulation (-) QoS	(-) regulation (-/+) QoS	(-) regulation (-/+) QoS
Secondary access	(-) QoS (-) Interoperability (-) complex	(-/+) QoS (-) Interoperability (-) complex	(-/+) QoS (-) Interoperability (-) complex

VII. CONCLUSION

In this paper, the perspectives of different actors concerning the available spectrum access options have discussed using a dual quantitative and qualitative research approach. In the quantitative study two deployment scenarios (macrocell vs. femtocell), to satisfy the coverage and capacity demand within one square kilometer business district, have been compared focusing on the spectrum demand. While in the qualitative study, the strategic business decisions of different actors (i.e. MNO and LNO) concerning the available spectrum access options have been discussed.

The carried analysis in this study underscored that the value of the spectrum vary according to the business setting and the deployment scenarios. Adding more spectrum bandwidth per radio base station in macrocell deployment scenario lead to noticeable reduction in the deployment cost compared to the case in the femtocell deployment. Moreover, the expected overall reduction in the deployment cost as result of using more spectrum bandwidth per site depends on the amount of the upfront spectrum fee. In this regards, MNOs tend to be unwilling to use dedicated licensed bands for indoor deployment, even if better QoS can be achieved. In other words the MNOs tend to be in favor of using more exclusive licensed bands for outdoor network deployment in order to sustain their competitive advantage and strategic position in the market. In the case of an independent LNO, the use of exclusive spectrum is faced by number of obstacles; i.e. availability, regulation constraints and the high spectrum fee. That is why independent LNOs will prefer to use unlicensed bands. Further on, LSA and secondary access could open new business opportunities for LNOs especially when certain technical and regulation hurdles are removed.

REFRENCES

[1] Z. Frias and J. Pérez, "Techno-economic analysis of femtocell deployment in long-term evolution networks," *EURASIP Journal on Wireless Communications and Networking,* vol. 2012, no. 1, pp. 1-15, 2012.

[2] D. H. Kang, K. W. Sung and J. Zander, *Cost Efficient High Capacity Indoor Wireless Access: Denser Wi-Fi or Coordinated Pico-cellular?,* arXiv:1211.4392 [cs.IT], 2012.

[3] FCC, "The Mobile Broadband Spectrum Challenge: International Comparisons Wireless Telecommunications Bureau Office of Engineering & Technology," FCC White Paper, 2013.

[4] S. N. Gupta, S. Abraham and Y. Gyulkhanda, "The center for Internet and Society," 24 June 2012. [Online]. Available: cis-india.org/telecom/unlicensed-spectrum-brief.doc. [Accessed 11 2 2013].

[5] J. Markendahl and M. Nilson, "Business models for deployment and operation of femtocell networks; - Are new cooperation strategies needed for mobile operators?," in *International Telecommunications Society (ITS),* Copenhagen , 2010.

[6] J. Zander and P. Mähönen, "Riding the Data Tsunami in the Cloud - Myths and Challenges in future wireless access," *IEEE Communications Magazine,* vol. 51, no. 3, pp. 145-151, 2013.

[7] S. Forge, R. Horvitz and C. Blackman, *Perspectives on the value of shared spectrum access, final report for the European Commission,* SCF Associates, 2012.

[8] P. L. Parcu, A. Nicita, G. Corda, M. A. Rossi and L. F. Bravo, "Authorised Shared Access (ASA): An Innovative Model of Pro-Competitive Spectrum Management," 1 May 2011. [Online]. Available: http://ssrn.com/abstract=2174518. [Accessed 3 June 2013].

[9] L. Simic, M. Petrova and P. Mähönen, "Wi-Fi, But Not on Steroids: Performance Analysis of a Wi-Fi-Like Network Operating in TVWS Under Realistic Conditions," in *IEEE International Conference on Communication,* 2012.

[10] J. Zander, L. Rasmussen, K. Sung, P. Mahonen, M. Petrova, R. Jantti and J. Kronander, "On the Scalability of Cognitive Radio: Assessing the commercial viability of secondary spectrum access," *IEEE Wireless Communications,* vol. 20, no. 2, pp. 28-36, 2013.

[11] M. Bennis and M. Debbah, "On spectrum sharing with underlaid femtocell networks," in *21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops,* Instanbul, 2010.

[12] Y. Bai, J. Zhou and L. Chen, "Hybrid Spectrum Usage for Overlaying LTE Macrocell and Femtocell," in *IEEE Communications Society subject matter experts for publication in the IEEE "GLOBECOM",* 2009.

[13] N. Shetty, S. Parekh and J. Walrand, "Economics of Femtocells," in *Global Telecommunications Conference, 2009,* Honolulu, 2009.

[14] M. B. Weiss and L. Cui, "The Hinges of Destiny: A Decision Analysis of Spectrum Users' Choices," in *IEEE DySPAN (Dynamic Spectrum Access Networks),* Bellevue, 2012.

[15] M. Barrie, A. Raju and S. Delaere, "Femtocell deployment strategies for MVNOs enabled by cognitive sharing," in *IEEE 23rd International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC),* Sydney, 2012.

[16] J. Xiang, Y. Zhang, T. Skeie and L. Xie, "Downlink Spectrum Sharing for Cognitive Radio Femtocell Networks," *IEEE Systems Journal,* vol. 4, no. 4, pp. 524-534, 2010.

[17] L. Huang, Z. Guangxi and X. Du, "Cognitive femtocell networks: an opportunistic spectrum access for future indoor wireless coverage," *IEEE Wireless Communications,* vol. April 2013, pp. 44-51, 2013.

[18] A. Durantini and M. Martino, "The spectrum policy reform paving the way to cognitive radio enabled spectrum sharing," *TelecommunicationsPolicy,* no. 37, pp. 87-95, 2013.

[19] S. Al-Rubaye, A. Al-Dulaimi and J. Cosmas, "Cognitive Femtocell, Future Wireless Networks for Indoor Applications," *IEEEVEHICULARTECHNOLOGYMAGAZINE,* no. March 2011, pp. 44-51, 2011.

[20] G. Gur, S. Bayhan and F. Alagoz, "Cognitive Femtocell Networks: an overlay architecture for Localized Dynamic Spectrum Access," *IEEE Wireless Communications,* no. August 2010, pp. 62-70, 2010.

[21] Plum Consulting, "Valuation of public mobile spectrum at 825-845 MHz and 870-890 MHz," A report to the Department of Broadband Communications and the Digital Economy, 2011.

[22] Australian Communications and Media Authority, "Opportunity Cost Pricing of Spectrum," Australian Communications and Media Authority, Canberra, 2009.

[23] C. Doyle, "International Telecommunication Union," January 2007. [Online]. Available: http://www.itu.int/osg/spu/stn/spectrum/ [Accessed 29 May 2013].

[24] J. Yeo, "Estimation of Bidder Valuations in an FCC Spectrum Auction," in *Financial Intermediation Research Society Conference,* Singapore, 2012.

[25] International Telecommunication Union, "Exploring the value and economic valuation of spectrum," ITU Telecommunication Development Sector, Geneva, 2012.

[26] T. Rosowski, T. Irnich, J. Kronander, E. Mohyeldin, K. J. Friederichs, K. W. Sung, H. Schotten, A. Apostolidis, K. Chatzikokolakis, P. Olmos and K. Konstantinos, "Initial description of the spectrum aspects of the selected scenarios," MEITS Internal Report, 2013.

[27] J. Zander and J. Markendahl, "Is there a Spectrum Shortage for Wireless Internet Access?," *Communications & Strategies,* vol. 90, no. 2nd quarter 2013, pp. 1-22, 2013.

[28] J. Zander and S.-L. Kim, Radio Resource Management in Wireless Networks, Artech House, 2001.

[29] B. Mölleryd and J. Markendahl, "Valuation of spectrum for mobile broadband services – Engineering value versus willingness to pay," in *22nd European Regional ITS Conference,* Budapest, 2011.

[30] B. G. Mölleryd and J. Markendahl, "Valuation of spectrum for mobile broadband services - The case of India and Sweden," in *Submitted to Telecommunications Policy,* 2013.