Cognitive Small Cell Deployment for Next Generation Wireless Systems

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Abstract

The upcoming decade is about to witness a tremendous growth in the popularity of smart devices. The integration of these enormous number of devices in the network poses a biggest challenge currently faced by the wireless society. To encounter this situation, ultra-densfication and spectrum extension are envisioned as the paramount solutions. Given the deployment costs and scarcity in the spectrum, these solutions appear to be indomitable. To overcome these bottlenecks, we propose a concept of cognitive small cell that jointly resolves the issues with small cell deployment and spectrum scarcity. In this article, we highlight the significant steps necessary for the deployment of this notion into 5G networks.

I. Introduction and Motivation

Since the invention of a smart phone in 2007, the mobile traffic has proliferated tremendously. Following the market analysis of mobile traffic done by CISCO [1], it is evident that this trend prevails also in future. Its a known fact that the state-of-art technologies (Multiple Input Multiple Ouput), waveforms (Orthogonal Frequency Division Multiplexing) and standards (Fourth-Generation (4G) – LTE, WiMAX) aren't capable of sustaining these demands in the upcoming decade. With this situation in hand, we are currently in the process of conceptualizing the requirements for the next generation wireless systems. Some important of these include: (i) the areal capacity in bits/m^2 must roughly increase by $1000\times$ compared to 4G, (ii) low latency $\approx 1\,$ms and, (iii) energy and cost efficient deployment [2].

In the recent past, Small Cell (SC) has emerged as a potential solution for coverage and capacity enhancements in a network. An SC represents a low power station that ranges from $10\,$m to $100\,$m, comparable to the size of a femtocell. The reduced transmit distance accomplished with the deployment of SCs enhances the link quality and aids spatial reuse [3]. As a result, ultra-densification via SCs is envisaged as an absolute paramount for the fifth-generation (5G) of wireless systems. Unfortunately, the capacity increases only linearly with the number of SCs, hence, it is implausible to procure the factor of 1000 in the areal capacity with ultra-densification alone. Additionally, backhaul deployment and operation of these substantial number of SCs are cost- and energy-intensive to the mobile operator. Complementing the link quality, the spectrum procures a large contribution to the areal capacity. Given the situation of the spectrum allocated for mobile communications, an extension in the available spectrum is imperative. In this regard, we propose the following classification to the spectrum extension: (i) ≥ 6 GHz; (ii) ≤ 6 GHz. The prime objective of this sort of classification is to shift the focus on the propagation characteristics and the issues thereof.

The spectrum beyond 6 GHz largely entails the milimeter Wave (mmW) is well-known for Point-To-Point (PTP). This range has been limited mainly to satellite or short range communications. In the recent past, it is envisaged as a powerful source of spectrum for the 5G systems. In present scenario, however, mmW technology is surmounted with the key-challenges like propagation loss, low efficiency of Radio Frequency (RF) component's such as power amplifiers, size of the antenna ($\lambda/2$ dipole) and link acquisition that need to be addressed. On the contrary, features like adaptive-beamforming are the key-enabler of this technology. In order to illustrate its feasibility, different scenarios have come forward to harmonize mmW spectrum into 5G, such as short range communications in a SC and wireless backhaul. Recently, Rappaport *et. al.* [4] resolved the propagation issues at 28 GHz and 38 GHz bands, this, however, raises a bigger question on its ability to sustain the mobility in communications. Therefore, to capture a deeper insight of its feasibility in 5G, it is essential to overcome the aforementioned challenges in the forthcoming future.

The spectrum below 6 GHz is utilized mainly for terrestrial wireless communication. Due to the static allotment of licenses by the regulatory bodies in this range, it is currently on the verge of scarcity. Given the spectrum is used efficiently, it is feasible to surmount this scarcity in the spectrum, for instance by means of secondary access. Cognitive Radio (CR), a concept introduced by Mitola in 1999 [5], is a suitable candidate that enable secondary access to the unused spectrum. Devices operating on CR principles acquire the capability of *learning* and *responding* to the changes in the environment. Although, in its original definition, CR embraces physical, medium access and application layers, however, in this article, we focus on the physical layer aspects.

For last one and a half decades, CR has engaged a large expertise of people from research, industry and regulatory bodies. Thereof, CR has found its niche in varied applications such as wireless microphones in TV white space and satellite communication [6]. Several organizations, mainly IEEE and European Telecommunication Standard Institute [7] has taken the responsibility of standardizing the CR technology. In the last years, this technology has evolved at a significant pace and has achieved a certain level of maturity. Hence, it is a rightful moment, where we should consolidate our efforts on dispositioning this technology in the 5G.

Following the previous discussion, it is evident that the spectrum extension and small cells are the key-enablers for the 5G system. Motivated by the fact, we propose a concept of Cognitive Small Cell (CSC), a promising approach that jointly enhance the small cell deployment and efficient usage of the spectrum below 6 GHz. In this regard, we aim to provide a deployment-centric viewpoint to ensure a successful integration of CSCs in the 5G network. Consequently, we consider the existing CR paradigms to enable secondary usage of the licensed spectrum.The feasibility of the respective paradigms are supported with hardware implementations.

The organization of the article is follows: Section II proposes a viable disposition of CSC in a 5G network. ~~In~~ Section III presents the deployment insights for the CSC. Particularly, an estimation model to characterize the true

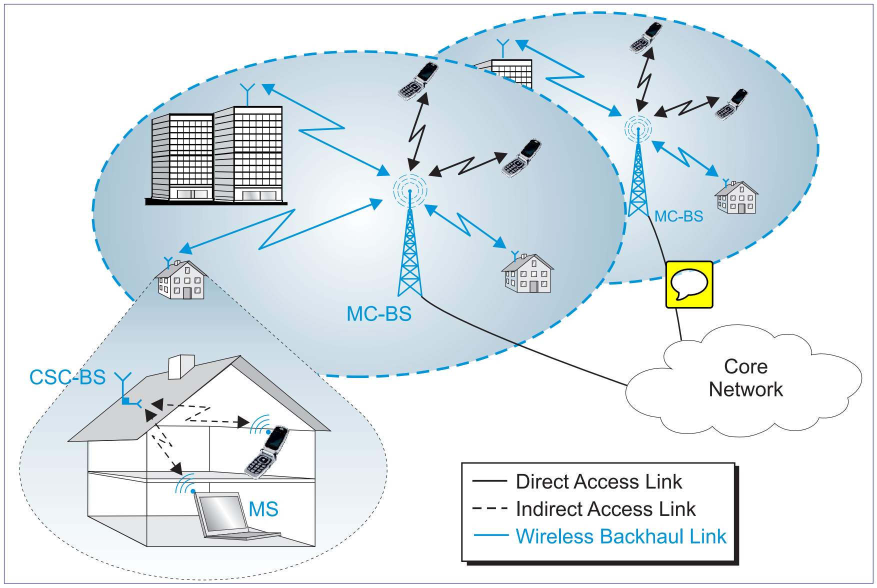


Fig. 1. An illustration of the cognitive small cell deployment in a 5G network.

performance of the CSC is proposed. Section IV and Section V evaluate~~s~~ the performance of CSC as interweave and underlay paradigms based on the estimation model, respectively. Section VI briefly discusses the open challenges involved. Finally, Section VII concludes the article.

II. Disposition of CSC in 5G network

This section illustrates the physical placement of CSC in a preliminary 5G architecture. It has been depicted that 70% of the data traffic is originated indoor [3]. In addition ~~to that~~, a new range of wireless services, categorized as Internet of Things, will operate from indoor. Thus, the effects will be far more consequential, if we consolidate these sources of data traffic by means of SCs deployment. In this regard, it is sensible to consider the residential and enterprise as the main deployment scenarios, cf. Fig. 1, for the CSC. Except for a different coverage regime, the operation principles of these scenarios are analogous.

Network Elements

For the disposition of the CSC in the network, the following key elements are essential: a CSC-Base Station (CSC-BS), a Macro Cell-Base Station (MC-BS) and Mobile Stations (MSs), cf. Fig. 1. MSs are the devices either served by MC-BS over a *Direct Access* (DA) link or the CSC-BS over a *Indirect Access* (IA) link. Furthermore, the MC-BS is connected to the several CSC-BSs over a *Wireless Backhaul* (WB) link.

Spectrum Access

In the proposed network architecture, the access to the spectrum is realized over the WB, the DA and the IA link.

1) A WB is a quasi-line of sight[1] PTP link between the CSC-BS and MS-BS that relays the backhaul traffic generated from the CSC to the core network. Accounting the feasibility of ultra-dense CSC, WB links presents a cost-effective and energy-efficient alternate to the mobile operator. Now, with limited infrastructure required for deployment, it accelerates installation and promotes scalability of the network. For the WB link, an exclusive spectrum for a longer duration is desired, hence, it is sensible to nominate a mmW band; or an exclusive band under 6 GHz can be acquired using the principles of Licensed Shared Access [7].
2) A DA link represents a direct access to the MS by the MC-BS over a licensed spectrum. The spectrum access for this link follows a conventional approach existing in the state-of-art wireless standards.
3) The CSC elements are responsible for executing secondary access to the licensed spectrum. The additional spectrum acquired is utilized for communications between the CSC-BS and the MS over the IA link, cf. Fig. 1.

Hardware Feasibility

Here, we outline the main aspects that pertain to the hardware realizability of the CSC. For CSC-BS, an antenna mount system consisting of an indoor and outdoor antenna is proposed. Whereby the indoor antenna exploits the walls of the building to physically separate the indoor transmissions over the IA link, in this way, it curtails the interference to the primary system and neighbouring CSCs. While, the outdoor antenna secures a narrow beam transmission to enhance the link quality for the WB link.

The Software Defined Radio (SDR) has played a vital role in the genesis of the CR [8]. Takinng this into account, we inherit the eminent features of SDR for the hardware deployment of CSC-BS and MS. Some of these include:

- Multi-channel support – To enable independent transmissions or reception of non-contiguous channels over the WB and the IA link.
- Real-time reconfigurability – With activation of Primary Users (PUs), the hardware should be able to reconfigure its RF parameters with minimum latency.

Network Compatibility

In addition to the secondary access, CSC has to co-exist harmoniously with the other elements existing in the network. After connecting to the near-by CSC-BS, the MS procures the control information (signalling and synchronization) over the IA link. To sustain a logical placement of CSCs inside the network, the CSC employs S1 and X2 interfaces over the WB link. For situations where several CBC-BSs co-exist under a MC-BS, operations like seamless cross-tier and co-tier handover will be a challenging task for the network.

III. Deployment Model (DM) for CSC

The performance characterization of a CR application is an interesting research problem. In this regard, mathematical models termed as baseline models are proposed [9]. These models are good for analysis, but in most cases they

[1] It allows limited number of objects between the direct link.

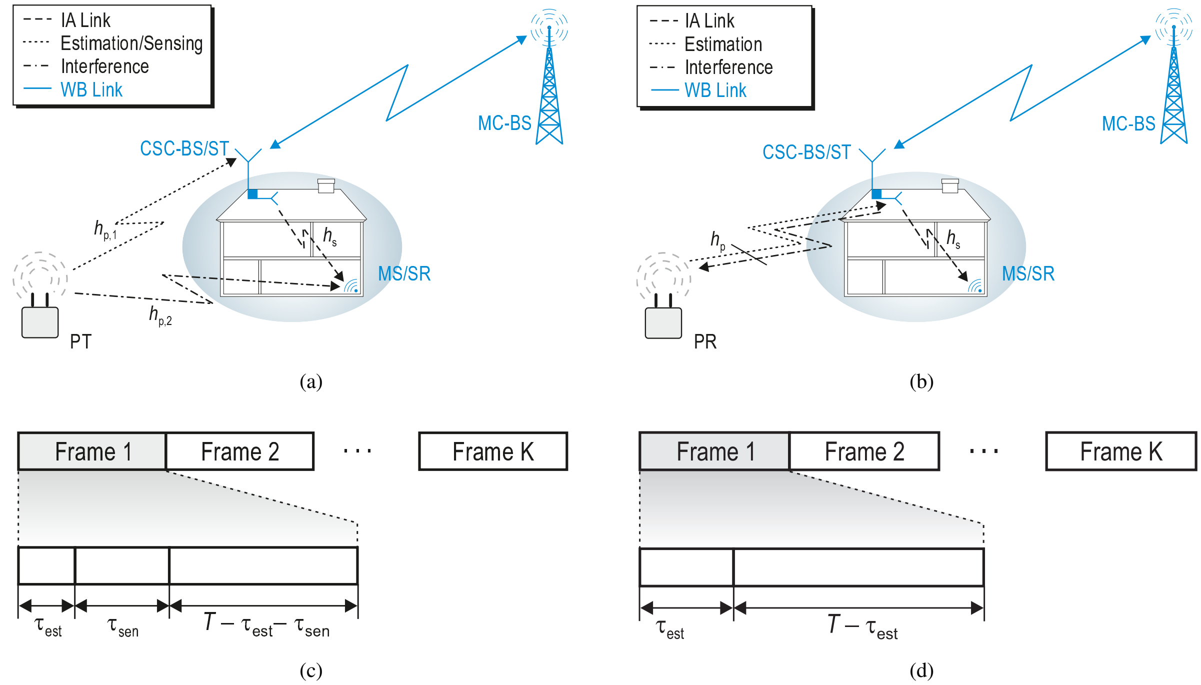


Fig. 2. An illustration of the deployment scenarios of CSC as IS (a) and US (b) depicting the interaction between the PU (PT or PR), the CSC-BS and the MS. Moreover, the CSC-BS as IS or US employs the PTA or the PRA as assistance strategy, respectively. (c) and (d) present their corresponding frame structures that includes the estimation of the received power, where τ_{est}, τ_{sen} and T represents the respective time intervals for estimation, sensing and frame duration.

assume the perfect knowledge of the system parameters. However, this situation is never encountered considering a hardware deployment. Thus, these models fail to capture the true performance of the CR system. Motivated by the fact, we propose a new model that integrates estimation of the unknown system parameters, thereby characterizes the true performance of CSC as a CR application. In the course of its discussion, we underline the caveats involved considering the deployment of the CSC. In the following segments, we briefly consolidate the prime ingredients required to characterize the proposed model:

CR Paradigms: Recently, Goldsmith *et. al.* [10] conceptualized different paradigms to promote secondary access to the primary spectrum: underlay, interweave and overlay systems. Of these, underlay and interweave systems are directly linked to the physical layer, whereas the overlay systems utilize advanced coding techniques that include the participation of higher layers. In the current scope, we limit our discussion to the underlay and interweave systems for the CSC deployment. The Interweave Systems (ISs) mainly consider Spectrum Sensing (SS) to detect the presence of a primary signal, whereas the Underlay Systems (USs) employ different mechanisms such as transmit power control that enable them to stay below a certain interference temperature. The CBS-BS and the MS employs either IS or US principles to perform secondary access to licensed spectrum. In this article, we emphasize the downlink transmission only, from CSC-BS to MS, cf. Fig. 1. Hereafter, for the downlink, the CBS-BS and the MS also symbolize the Secondary Transmitter (ST) and the Secondary Receiver (SR), respectively.

In spectrum sharing, protecting the Primary Receiver (PR) against interference is the biggest challenge. Both paradigms implement~~s~~ different strategies to address the interference at the PR. Whereby, the IS renders an interference-free, while promises an interference-tolerant access to the primary spectrum.

Assistance Strategy: Irrespective of the underlying paradigm, it is complementary for the ST to acquire assistance either from the Primary Transmitter (PT) or the PR, hence, categorized as PT Assisted (PTA) and PR Assisted (PRA) [11]. According to PTA, the ST listens to ~~the~~ transmission from the PT. While for PRA, the ST aligns itself to ~~the~~ transmission from the PR, this transmission is present either on the channel of interest or on a separate control channel. In order to exploit the channel reciprocity principle for the later case, the coherence bandwidth needs to be greater than frequency separation between ~~the~~ two channels.

Performance Parameters: These parameters characterize the performance of the CSC by means of the interference induced and the throughput attained in the primary and secondary system, respectively.

System Parameters: The performance parameters – depend on; are represented as functions of, the system parameters. In order to keep the performance analysis for the DM consistent with the majority of wireless standards, we select received power at the ST as the system parameter.

Propagation Channel: Due to the presence of thermal noise and propagation channel in the system, the ST encounters fluctuations in the received signal. Although, there exist imperfections at the RF-end: DC-offset, I/Q imbalance and non-linear RF components, that need to be addressed. However, in the current scope, we would capture the effects from the noise and the channel in the system only.

Fading causes variations in the channel gain, thereby leads to variations in the received power. To undermine the effect of these variations, it is essential to consider time-slotted transmissions at the ST. Thus, at the system design, the frame duration is held equivalent to the coherence time of the channel. With this, each frame witness a different realization of the channel gain.

Estimation: Given the knowledge of the received power at ST, it is straightforward to depict the performance of the system. However, as the channel gain varies independently, this knowledge is basically not available at the ST. Hence, through estimation of the received power corresponding to each frame, the ST periodically updates the knowledge of the channel gain. In this context, a short interval within each frame is dedicated to the estimation of the system parameter, cf., Fig. 2c and Fig. 2d. Therefore, we introduce the estimation of received power in the system model.

With the introduction of the estimation at the ST, a certain distortion is induced in the system. This distortion, if not considered in the system model, leads to harmful interference at the PR. The severity in distortion is characterized based on the probability of confidence and the estimation time. Particularly, it is important to select the estimation time appropriately such the distortion doesn't exceed beyond a certain level. Consequently, the estimation time causes the throughput to deviate from its ideal case. The ideal case illustrates the situation with perfect knowledge of the receiver power.

Hence, from the deployment perspective, it is essential to include these ingredients in the model. Subsequently, we employ the EM to the aforementioned paradigms and characterize the true performance of the CSC.

TABLE I

PARAMETERS FOR NUMERICAL ANALYSIS

Parameter	Paradigm	Value
Sampling frequency	US, IS	1 MHz
Frame duration	US, IS	100 ms
Estimation time	US, IS	10 ms
Probability of confidence	US, IS	0.95
Noise power (PU, ST, SR)	US, IS	−100 dBm
PU transmit power	US, IS	0 dBm
Path loss ($h_{\mathrm{p},1}, h_{\mathrm{p},2}$)	IS	100 dB
Path loss (h_{p})	US	100 dB
Path loss (h_{s})	US, IS	80 dB
PU Channel occupancy	IS	20%
Interference temperature	US	−110 dBm

IV. CSC AS INTERWEAVE SYSTEM

The CSC-BS as IS employs SS to determine the presence or absence of the primary signal in time, frequency and space domain. Although, several techniques such as energy detection (ED), matched filtering, cyclostationary, feature-based detection exist, however, due to its versatility towards unknown primary signals, ED is widely investigated in the literature. According to ED, the ST performs hypothesis testing by listening to the transmission from the PT. Subsequently, the received power is compared to a threshold. In this way, the ST is able to protect the PR against interference. Based on the discussion, it is reasonable to employ PTA at the ST as IS, cf. Fig. 2a.

The probability of detection ($\mathrm{P_d}$) and probability of false alarm ($\mathrm{P_{fa}}$), represent the sensing errors, limit the performance of the system. To ensure an interference-free transmission, the ST must sustain a minimum level of $\mathrm{P_d}$. With the knowledge of the received power, it is feasible to determine an optimum sensing time and the threshold [9]. In a real deployment, this knowledge however is not available at the ST. In this regard, we propose a new frame structure, cf. Fig. 2c, that includes the received power estimation [12]. The estimation is followed by the sensing and the data transmission.

Next, we investigate the effect of estimation on the performance of the IS. Fig. 3a presents the distortion in $\mathrm{P_d}$ (by means of upper and lower bound[illegible]rses the estimation time for different values of received SNR at the ST, where $\mathrm{P_d} = 0.9$ is desired. For a certain choice of probability of confidence ($\mathrm{P_c}$), the confidence intervals for the estimated received power can be determined. These intervals translate to the distortion in $\mathrm{P_d}$. It is worthy to note that distortion becomes intolerable for low value and negligent for high value of [illegible]ived SNR. Fig. 3b depicts the throughput verses received SNR, where estimation time equals 10 ms and optimum sensing time. The case with $\mathrm{P_c} = 0$ illustrates a situation under which the estimation of the received power is included in the system but it is

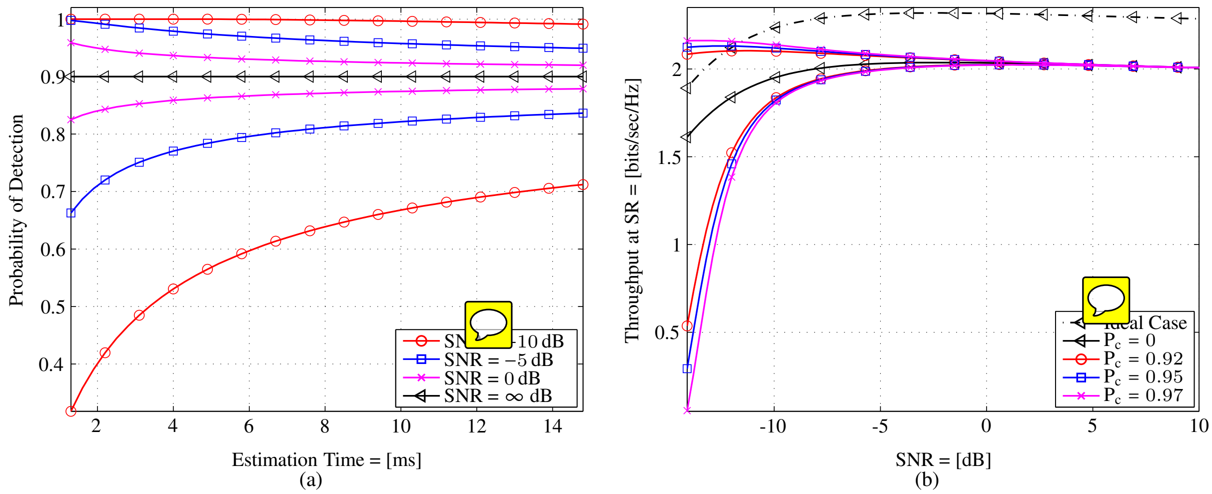


Fig. 3. (a) The distortion in probability of detection versus the estimation time for different received SNR $\in \{-10, -5, 0, \infty\}$ dB. (b) The distortion in throughput at SR verses the received SNR with $P_c \in \{0, 0.92, 0.95, 0.97\}$, estimation time $= 10$ ms and optimum sensing time [12].

perfect. Moreover, Fig. 3b illustrates its deviation of throughput at SR from the ideal case (with no estimation). Hence, based on this characterization, it is feasible to define an operation regime of the CSC-BS in terms of received SNR by selecting the P_c and estimation time appropriately.

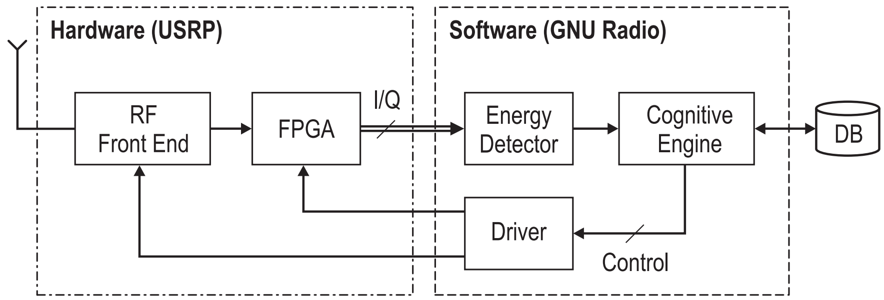
Proof-of-concept

A hardware demonstrating the feasibility of the CSC-BS as IS is depicted in Fig. 4 [13]. An SDR based platform, cf. Fig. 4a, is utilized to sense multiple non-contiguous GSM 1800 MHz downlink channels Fig. 4b. In this scenario, the GSM base stations are categorized as PTs. A database is installed to access the GSM channel list and to store the binary values corresponding to each channel. To include SS over a wide spectrum, we deployed SS through frequency-hopping. A cognitive engine that enables learning based on the channel occupancy is a subject of future research.

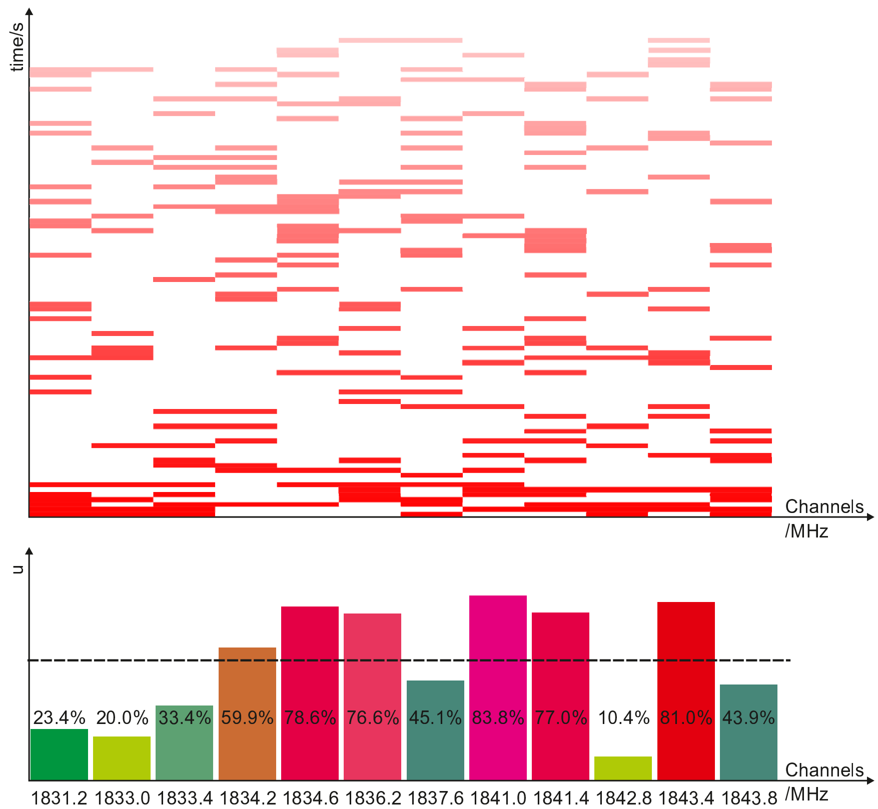
V. CSC AS UNDERLAY SYSTEM

According to the US, it is permissible for CSC-BS to transmit in the frequency bands where PU is active. This property where PU are susceptible to a certain level of interference results in better utilization of the spectrum resources. Transmit power control is one such mechanism by which the ST is able to sustain its transmit power below interference temperature (IT) defined for the PR. Although, it is feasible to execute the power control based on either PTA or PRA, however, for the analysis, we apply power control subject to the PRA.

Now, to execute the power control, the ST needs the knowledge of the channel between the ST and PR. This information is acquired by listening to a beacon or a pilot channel transmitted by the PR. In this way, the ST performs channel estimation based on the received power. Likewise IS, a new frame structure that includes estimation time



(a)



(b)

Fig. 4. (a) A hardware and software interface of a SDR based demonstrator depicting the CSC-BS as IS. (b) A snapshot of the Graphical User Interface of the demonstrator, whereby the slices (red and white) represent the channel occupancy corresponding to a single measurement at a given time instant. The bar plots illustrate the channel occupancy (u) for each channel with a history of 500 measurements.

followed by data transmission is proposed at the ST, cf. Fig. 2d. Apparently, limited estimation time leads to variations in the received power, thereby the variations are induced in the controlled power at the ST. This causes the power received at the PR to deviate from the IT. Unless investigated, these variations may lead to harmful interference at the PR. Hence, based on the P_c, we capture the variations in the received power at the PR across the IT.

Analog to IS, we analyze the effect of estimation on the performance of the US. Fig. 5a illustrates the dependency

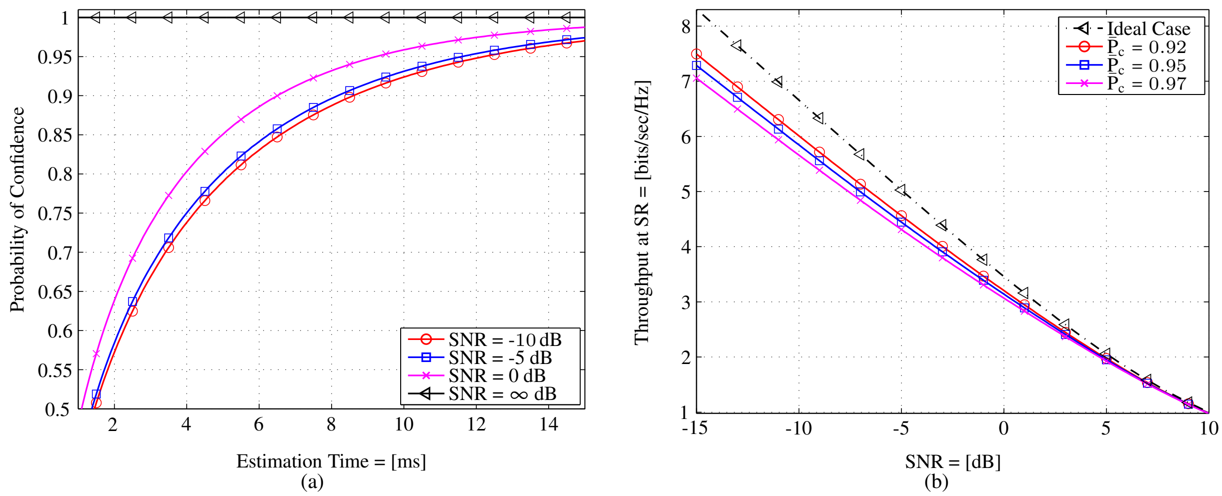


Fig. 5. (a) The probability of confidence versus the estimation time for different received SNR $\in \{-10, -5, 0, \infty\}$ dB. The $\mathrm{P_c}$ captures the severity of distortion in the power received at PR. (b) The distortion in the throughput at the SR verses received SNR for different $\mathrm{P_c} \in \{0.92, 0.95, 0.97\}$ and optimum estimation time [14].

of the $\mathrm{P_c}$ on the estimation time and received SNR. With the motivation of capturing the interference at the PR, a certain level of $\mathrm{P_c}$ across the IT is acquired. Hence, an appropriate choice of estimation time is obligatory for the system. For instance, with received SNR = $0\,\mathrm{dB}$ and $\mathrm{P_c} = 0.95$, the estimation time corresponds to $\approx 9.2\,\mathrm{ms}$. Next, Fig. 5b represents the variation of the throughput at the SR verses the received SNR for different $\mathrm{P_c}$, where estimation time is selected optimally. Moreover, Fig. 5b depicts a margin between the ideal case (with no estimation) and the EM, this margin increases with decrease in received SNR. Based on the analysis, it is worthy to note that the ideal case overestimates the performance, hence, doesn't characterize the true performance of the US.

Proof-of-concept

A hardware realization illustrating the feasibility of the US were presented in [15], whereby the major challenges involved while building a prototype were investigated. An SDR based platform was installed to depict the variations in the propagation channel $(h_\mathrm{p}, h_\mathrm{s})$, cf. Fig. 2b. These variations, subject to the mobility of the PR and the MS, were captured and validated based on the analytical expressions. For simplification, a constant transmit power was considered at the CSC-BS. However, it will be interesting to demonstrate the power control mechanism over an SDR based platform.

VI. Overview of Key Challenges

In this section, we briefly investigate some of the major key challenges that are subjects of future research.

Network-centeric interference managment: In this article, we investigated the performance of CSC based on a single CSC-BS and a PU. However, the interference from the neighbouring CSC-BS PUs was excluded in the analysis. Therefore, to characterize the interference in the network, the stochastic geometry is recently employed for modelling the locations of the primary (PT, PR) and secondary systems (CSC-BS, MS). Thereby, depicting the performance of CSC based on the underlying paradigm posses a great challenge.

Quality of Service (QoS) for CSC: The throughput, an important performance parameter, characterizes the QoS inside the CSC. Now, to decide upon the channels in the database subject to a certain QoS, it is essential to evaluate the throughput at the CSC-BS. In this regard, it is necessary to estimate: $h_{\mathrm{p},2}, h_{\mathrm{s}}$ for IS and; h_{s} for SU at the MS, and fed back to CSC-BS through a reverse channel. Therefore, to characterize the distortion induced due to the estimation at the MS presents an interesting problem.

VII. Conclusion

Contributing to the 5G evolution is an exciting moment for the communication engineers. The ultra-densification and the spectrum, constituting the largest portion of the desired areal efficiency, are envisioned as the key-enablers for the 5G systems. These solutions are, however, faced with the high deployment costs and the limited spectrum, thus, hinder the deployment of the SCs. Driven by this fact, we proposed the concept of CSC that resolves the problem of a small cell deployment and scarcity in spectrum. In this article, it has been motivated that CSC has the necessary credentials to accomplish the requirements for the next generation of wireless systems.

References

[1] CISCO, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2013–2018," *White Paper*, February 2014.

[2] J. Andrews *et al.*, "What Will 5G Be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, June 2014.

[3] V. Chandrasekhar, J. Andrews, and A. Gatherer, "Femtocell Networks: A Survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59–67, September 2008.

[4] Rappaport *et al.*, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[5] J. Mitola and J. Maguire, G.Q., "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug 1999.

[6] S. Sharma, S. Chatzinotas, and B. Ottersten, "Cognitive radio techniques for satellite communication systems," in *Vehicular Technology Conference (VTC Fall), 2013 IEEE 78th*, Sept 2013, pp. 1–5, (Invited paper).

[7] ETSI TS 103 113, "Electromagnetic compatibility and Radio spectrum Matters (ERM); System Reference document (SRdoc); Mobile broadband services in the 2300 - 2400 MHz frequency band under Licensed Shared Acces regime," July 2013.

[8] F. K. Jondral, "Software-defined radio-basic and evolution to cognitive radio," *EURASIP Journal on Wireless Communication and Networking*, 2005.

[9] Y.-C. Liang *et al.*, "Sensing-Throughput Tradeoff for Cognitive Radio Networks," *IEEE Transactions on Wireless Communications,*, vol. 7, no. 4, pp. 1326–1337, April 2008.

[10] A. Goldsmith *et al.*, "Breaking Spectrum Gridlock With Cognitive Radios: An Information Theoretic Perspective," *Proceedings of the IEEE*, vol. 97, no. 5, pp. 894–914, May 2009.

[11] X. Song *et al.*, "Spatial throughput characterization in cognitive radio networks with threshold-based opportunistic spectrum access," *Selected Areas in Communications, IEEE Journal on*, vol. 32, no. 11, pp. 2190–2204, November 2014.

[12] A. Kaushik *et al.*, "Sensing-Throughput Tradeoff for Cognitive Radio Systems with Unknown Received Power," *CROWNCOM*, April 2015, (submitted).

[13] A. Kaushik, M. Mueller, and F. K. Jondral, "Cognitive Relay: Detecting Spectrum Holes in a Dynamic Scenario," in *Proceedings of the Tenth International Symposium on Wireless Communication Systems (ISWCS 2013)*, Apr. 2013, pp. 1–2.

[14] A. Kaushik *et al.*, "Estimation-Throughput tradeoff for underlay cognitive radio systems," *IEEE ICC 2015 - Cognitive Radio and Networks Symposium (ICC'15 (12) CRN)*, Jun. 2015, (to appear).

[15] A. Kaushik, M. R. Raza, and F. K. Jondral, "On the Deployment of Cognitive Relay as Underlay Systems," in *CROWNCOM*, Jun. 2014.