Planning of Ultra-Dense Wireless Networks

Anwer Al-Dulaimi, Saba Al-Rubaye, John Cosmas, and Alagan Anpalagan

Abstract

Fifth generation (5G) wireless networks adopt the deployment of ultra-dense small cells for efficient slicing of radio resources. This conceptual change in network structure aims to meet the rapid increase in mobile data traffic and connected devices. However, limited free spectrum and dynamic assignment of resources are main concerns when considering the cognitive small cells solution. Therefore, there is a need to map traffic patterns with the number of cognitive small cells to provide an optimized network architecture operating with adequate spectrum resources. This article investigates the case when network densification exceeds the radio resource capacity, causing a large scale overlapping in cell coverage area and used channels. Taking into consideration cognitive network performance characteristics, we identify two spectrum coexistence frameworks, *Space Filling* and *Time Filling*, to improve spectrum utilization and scalability for moderately large networks. Simulations show that there is a turning point when network performance starts to decline as the number of cognitive small cells exceeds the shared resources in a site area, subject to a certain load profile. This optimization of network structure, based on spectrum transmission opportunities, brings about a new topic for operators and research communities considering small cells operating in the unlicensed band.

Introduction

Cognitive wireless networks enable dynamic access to underutilized spectrum in the licensed band. This type of network provides higher values for data rates and capacity, as users tend to download data instead of making voice calls, using enhanced radio access and decision making techniques [1]. Spectrum efficiency is determined by a variety of parameters such as successful assessment of channel availability, selection of suitable and short transmission links, and traffic distribution between site access points. Therefore, user association and access point selection are key features for ultra-dense radio networks employing distributed small cells. Specifically, these features can reduce the impacts of overlapped coverage areas, and also determine the instantaneous power of access points in multi-shaped coverage areas as provided by the IEEE 802.22 standard for cognitive wireless regional area networks (WRANs) [2]. The assumptions of spectrum shortage and the high-cost of deploying access points, in known network design paradigms, have impacted the network structure of the current cellular systems such as fourth generation (4G) Long Term Evolution (LTE) standards [3]. Therefore, LTE networks are designed with relatively large sized coverage areas to operate at the upper bound limits of spectrum efficiency [4]. This leaves less margin for any new developments using the licensed band while motivating the dense deployment of small cells operating in the unlicensed band.

In cognitive radio communications, the small cell solution is driven by the theoretical approach of intensive network slicing provided with new spectrum coexistence techniques for efficient spectrum utilization [5], as shown in Fig. 1. This also requires efficient spectrum sensing mechanisms and instant sharing of sensor information between contiguous small cells [6]. Moreover, small cells can improve users' connectivity in heterogeneous networks (HetNets) through shorter wireless links of optimal pilot power. Currently, wireless networks employ predefined converged small cells [7], without considering the challenges that may emerge when deploying a large number of similar cells at the same sites. Cognitive radio small cells impose additional challenges because of their opportunistic spectrum access and flexible coverage areas. Therefore, mobile operators need to consider new spectrum coexistence models when sharing the spectrum with other users regardless of being the owners of the spectrum band.

Resource allocation provides users with the necessary spectrum considering the requested quality of service (QoS), assigns users between different tiers, and enables high volumes of data delivery to end users. Most of the resource allocation approaches for cooperative cognitive radio networks are presented without much consideration for overlapped small cell domains or shared use of channels between cognitive radio users [8]. In fact, the trend in the literature seems to be focused on improving the allocation of radio resources in cellular networks consisting of overlaid small cells to deal with the challenge of limited backbone capacity. In the cognitive radio context, this may happen when small cells release channels back to the main network or neighbored cells as soon as they fulfill a transmission request. To achieve this, cognitive small cells needs to employ an efficient medium access control (MAC) mechanism that can adaptively access available channels without interfering with the surrounding wireless environment. Both network planning and spectrum availability need to be combined to efficiently utilize the scarce radio resources by deploying the optimal number of cognitive small cells. This defines why we need to jointly consider the impact of small cell deployment and the resource allocation problem in two-tire networks, rather than separately.

Digital Object Identifier: 10.1109/MNET.2017.1500258NM

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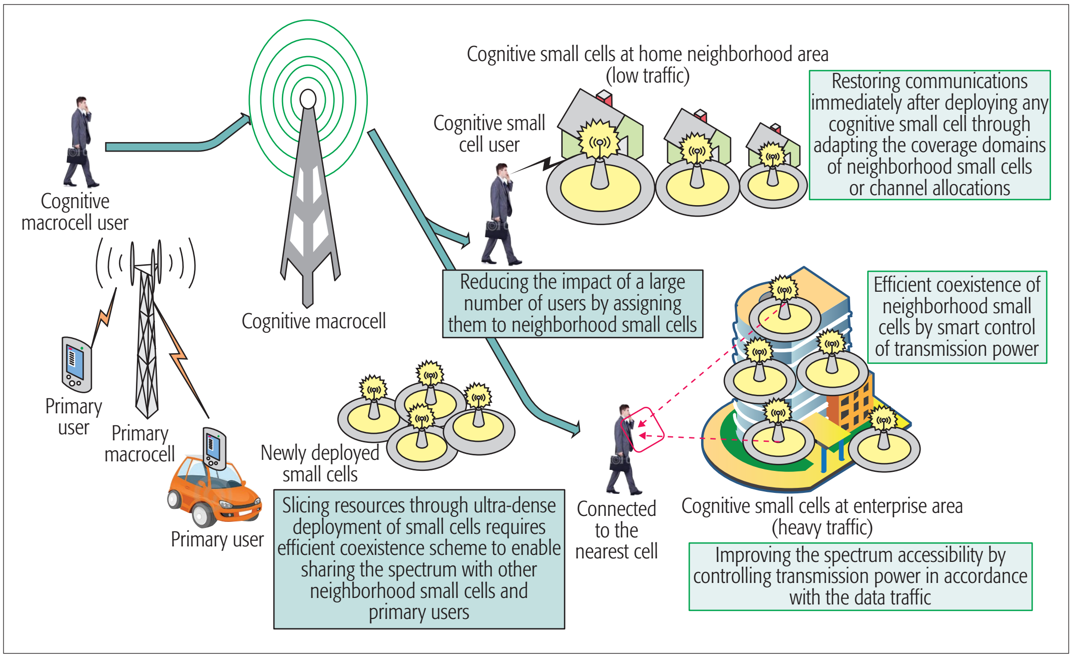

FIGURE 1. Cognitive small cells deployments in existing network infrastructure.

Mobile operators recognize that satisfactory services can be achieved by employing a sufficient density of access points in any network site area. In this article, we believe it is time to move another step forward by addressing the impact of having overly deployed small cells on the provided services. In this regard, we evaluate the optimal values of small cells deployed among the relevant macrocells to accomplish the necessary network density that provide the requested user services. Small cell deployment usually implies advanced coexistence techniques, as analyzed in our previous work [9]. However, different techniques for small cell coexistence are proposed and evaluated in such a two-tier HetNet. To the best of our knowledge, none of the existing literature maps the density of the deployed small cells to the pattern of available free channels accessed by cognitive radio communications. This article characterizes the cognitive radio network architecture by addressing the following questions:

- What is the optimal number of cognitive small cells that can be deployed under the umbrella of a cognitive macrocell coverage area?
- How to improve resource allocation and spectrum coexistence for ultra-dense networks employing cognitive small cells?

The rest of this article is organized as follows. The next section presents the major issues still to be solved with small cell deployment. Then, new coexistence schemes are proposed for cognitive small cells, namely *Space Filling* and *Time Filling*. The optimal planning of cognitive small cell deployment is verified through spectral capacity analysis, as shown in the latter section, followed by concluding remarks in the final section.

Challenges in the Deployment of Small Cells

Spectrum scarcity and increasing capacity demand require macrocells to share their spectrum band with small cells, making all channels universally available for the entire cognitive radio network. To enable such spectrum sharing, the following challenges should be taken into consideration in any potential deployment of cognitive radio small cells.

> The small cell solution is driven by the theoretical approach of intensive network slicing provided with new spectrum coexistence techniques for efficient spectrum utilization.

Dynamic Resource Allocation: Dynamic resource allocation starts by scanning the spectrum to detect spectrum use so free channel intervals can be identified. The accuracy of obtained sensing reports on channel status may be impacted by local shadowing phenomena, causing interference to occur. Therefore, cooperative sensing schemes and sharing knowledge on channel availability between small cells are the main solutions from a network high-level perspective. In addition, improving the sensing mechanisms through more sophisticated sensing intervals may significantly improve the allocation of resources from a system-level perspective. Novel resource allocation should allow more slicing of any radio resources with a decision making model for friendly coexistence of multi-users on adjacent channels or even the same channel [10].

Deployment and Backhaul Design: The impact of spectrum access control is particularly substantial in HetNets employing macro and small cells. Macrocell networks can access more spectrum by deploying colocated small cells operating in the unlicensed band, causing a series of changes in signaling control between different cell domains. Therefore, it is essential to have an architectural network design that integrates multi-radio interface technologies (heterogeneous hardware) to operate as a homogeneous infrastructure.

Interference Management: In real network deployments, the uncoordinated deployment of small cells is one of the major reasons for increasing interference in ultra-dense networks. This situation is escalated with cognitive small cells

In overlapped space-filling scheme, cognitive small cells can overlap their coverage areas with their neighbor cells.

because of the overlap between this type of cell in channels and domains. The impact of interference depends on the transmitted power, used bandwidth, cell density, and used mechanism for channel access. Nevertheless, there are a few mitigation techniques for interference cancellation such as adaptive power, beamforming, and precoding techniques. All of these techniques imply changes in either macrocell or small cell coverage areas.

Spectrum Efficiency: Channel management is one of the main features for dynamic spectrum access compared with the existing mobile networks. Spectrum technology deployment is growing faster than the determination of spectrum availability. Thus, as frequency bands or free white holes become more scarce and unavailable for the next generation of wireless technologies, a wide range of services will require radio spectrum as a resource to operate properly. This drives industrial and research communities to consider developed radio interfaces and infrastructural wireless variations to improve spectrum access and allocation.

Transmitting over Different Licensed/Unlicensed Bands: The aggregation of licensed and unlicensed bands makes it possible to increase user throughput and improve connectivity. Therefore, the spectrum decision functionality in any cognitive small cell allows simultaneous access to licensed and unlicensed bands. However, user control and managing channel accessibility in dense networks become complicated with the absence of a defined model for network structure. As a solution, cognitive small cells can be integrated with the cellular network provided with necessary decision making entities that consider a collection of cognitive radio network principles, including learned or exchanged information.

Spectrum Coexistence of Small Cells

Small cell coexistence was studied in the literature considering a fixed spectrum assignment in licensed networks with guaranteed QoS. Tailoring to cognitive radio communications, this section studies cognitive small cell coexistence in a dynamic spectrum access model.

Space Filling

Cognitive radio networks are likely to adopt the conventional cellular network structure of fixed sized macrocellular areas. In this network modeling, we assume that there is always a chance to deploy more small cells inside a defined macrocell area, as shown in Fig. 1. We analyze two schemes for the coexistence of small cells:

Non-Overlapped Space Filling: In this scheme, cognitive small cells coexist within the same site without overlapping their domains. Inspired by cell breathing in traditional wireless networks, cognitive small cells have to shrink their transmission domains whenever a new small cell is being deployed in the network site. As a result, the macrocell may contain dissimilar sub-cells of small cells subject to their coverage areas. This heterogeneous inconsistent sequence of variable sized small cell areas can be in a contiguous or noncontiguous order. To ensure fair spectrum coexistence, cognitive small cells may use adaptive frequency reuse techniques in a cellular orthogonal frequency division multiple access (OFDMA) system. The coexistence is performed using a frequency reuse model that can mitigate interference and improve spectrum access [11]. This transmission technique can be used to reduce competition for resources between neighbor small cells, protect the primary users, and reduce the risks of hidden terminals. The major challenge from a cognitive radio perspective is the arbitrary allocation of coverage areas between small cells. This can be performed using one of two methods: first, autonomous cognitive macrocell, which can manage the area allocation and channel sharing between various small cells. The common control channels [12] can be used to perform such operations between neighboring small cells in a distributed and localized manner. This scenario requires the macrocell to be aware of any newly deployed small cells. Second, we assume that the small cells use sensing to perform the necessary coexistence adaptations, and that the macrocell has no prior knowledge of any small cells on the way for deployment. Therefore, accurate and efficient agile sensing is critical to avoid any interference/interruption in services during-time and post-time of the new small cell deployment.

Overlapped Space-Filling: In this scheme for small cell deployment, we assume that small cells can overlap their coverage areas with their neighbor cells. This makes spectrum coexistence more challenging because of the redundant frequency adaptations of mobile users moving between these overlapped transmission domains. Generally, this scenario can be employed while deploying small cells that belong to different cognitive operators in the same site. Spectrum reuse is used to avoid interference between contiguous cells where no adjacent cells may concurrently transmit over the same channels. Therefore, channels will be allocated more dynamically between different cells as more new small cells are deployed in the network. Channel assignment control can be provided by the macrocell backbone for exchanging information on network structure changes. This will reduce the possibility of having interference and helps utilize spectrum at the network level.

To model the changes in the coverage area of a cognitive small cell in response to the deployment of a new neighbored small cell, we assume that a macrocell is located along the X-axis with a domain area of πR^2, as shown in Fig. 2. Then, a small cell of diameter $2r$ is deployed along the macrocell axis. At the time t, the probability that the small cell will remain at the same size is $\mathcal{P}[\phi]$. We define two cases here: case (1) shown in Fig. 2a where the small cell area diameter $\mathcal{D}$ shrinks to $0 \leq \mathcal{D} \leq 2r$, and case (2) shown in Fig. 2b, where the small cell area diameter shrinks again to $0 \leq \mathcal{D} \leq r$. Then, $\{\phi\}$ is a function for the small cell area diameter at a certain time and can be given as $\mathcal{F}[T \geq t \backslash \mathcal{D}$, where t is the time before a small cell adapts its coverage area to a new area size.

The conditional probability for a small cell to have a certain coverage area $\mathcal{P}[\chi]$ is a function of time and is given as

$$\mathcal{P}[\chi] = F[T \geq t] = \int_a^b p(s)\mathcal{P}[\phi]ds \tag{1}$$

where p(s) is the probability density function for the number of small cells within a macrocell area; and *ds* is the variation in the number of small cells, *a* is the time when a new small cell is being deployed inside the macrocell area, and *b* is the time when the new small cell is fully deployed and starts functioning.

As the cognitive small cell adapts its coverage area from time to time because of the newly deployed small cells, there is a chance of losing communications with end users. This may happens when a small cell domain shrinks away from a connected subscriber, as shown in Fig. 2c. The probability that a subscriber, located at point (*X*, *Y*), falls inside the small cell coverage area is denoted as the probability of the small cell coverage $F\ [T \geq t \setminus (X, Y)]$. Then, the coverage probability for a small cell that undergoes area coverage adaptation is given as

$$\mathcal{P}[\chi] = \int_a^b \int_0^s p(X,Y)\mathcal{P}[\phi]dXdY \tag{2}$$

where p(X, Y) is the probability density function for a small cell coverage area at location (*X*, *Y*).

It is worth mentioning that increasing the number of small cells may impact user mobility and increase handoffs, which is beyond the scope of this article.

Time Filling

In this scheme, small cells can be distributed randomly along the macrocell area with the possibility of overlapped coverage areas and shared spectrum usage. Time filling of the spectrum may be enabled by the 802.11 wireless local area network (WLAN) that determines local access to unlicensed spectrum in small domains such as home and enterprise sites [13]. The 802.11 MAC employs carrier sense multiple access with collision avoidance (CSMA/CA) for medium access. This technology enables listening to the channel for certain time intervals before transmitting [14]. The protocol scans the selected channel prior to any transmission to prevent collisions using a backoff counter. The 802.11e standard considers high-priority traffic for transmissions using the distributed coordinator function (EDCF) mechanism. This means that access points with lower priority traffic will back off for longer intervals to start a transmission. This mechanism reduces the possibility of collisions and improve the performance of real-time traffic [15].

Different channels are accessed by users at various times and locations to perform transmissions between access points and mobile subscribers subject to the requested services, number of active users, used technologies, and spectrum assignment at various geographical locations. As secondary users for the spectrum, cognitive small cells may employ a developed scheme for adaptive frequency reuse. Specifically, each small cell is designated to share one channel at a time with the primary network, as shown in Fig. 3. However, this model of slicing resources is unlikely to be employed in network infrastructures that consist of ultra-dense very small sized cells. In fact, this coexistence scheme is just another model of fixed spectrum assignment that limits spectrum trading between different users. The time filling scheme imposes more complexity for operators when considering shared spectrum to meet high traffic requirements. Also, there might be some additional challenges for network performance when more deployed cells try accessing the spectrum band. This means cognitive small cells have only a limited number of free time intervals at any used channel in their resource area. In such a fragmented and scattered network model of small cells employing partial capacity of the operational channel, it is very hard to predict performance when deploying lots of new small cells.

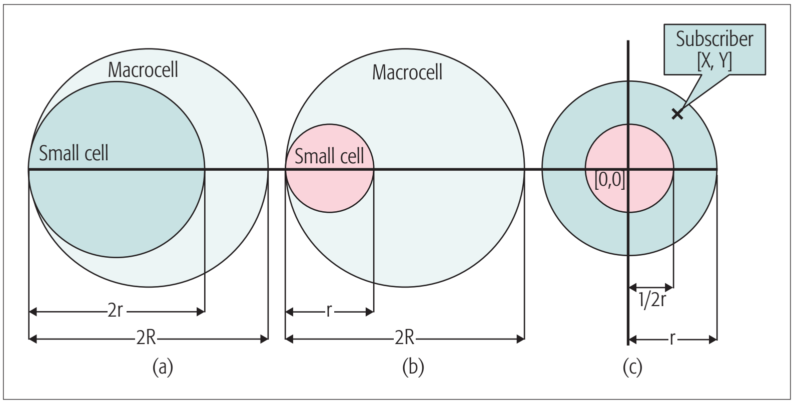

FIGURE 2. The adaptation of small cell coverage area: Case (A): small cell diameter is 2r, Case (B): small cell diameter is r, Case (C): subscriber coverage analysis.

To model the time filling scenario, the conditional probability $\mathcal{P}[\mathcal{Q}]$ for a small cell to transmit on slot time *t* of channel *i* is assumed to be

$$\mathcal{P}[\mathcal{Q}] = \int_a^b p(t)\mathcal{P}[\mathcal{L}_i]dt \tag{3}$$

where p(t) is the probability density function for the number of small cells conducting transmissions at the same time. $\mathcal{P}[\mathcal{L}_i]$ identifies the probability that a small cell is using channel *i*, as $\mathcal{P}[\mathcal{L}_i] = \mathcal{F}\ [T \geq t : i]$.

The target application for the cognitive radio network is to utilize all the spectrum channels as one pool. Therefore, the cognitive radio network should be able to adapt and transmit using any channel when adhering to the coexistence etiquettes and requested QoS. In this case, an individual cognitive small cell may decide to transmit according to the local wireless situation. In dense/distributed small cell deployments, it is almost impossible to define a solution for accessing a reserved spectrum due to the independent model of channel assignment. Accordingly, small cells will always try to access the spectrum in a competitive mode rather than a collaborative mode. In our analysis, we assume no limits on the number of newly deployed small cells, as such deployments may be performed by users rather than operators. Therefore, it is logical to expect that small cell deployments will mostly occur at network sites with higher traffic demands. This causes imbalance between traffic control models

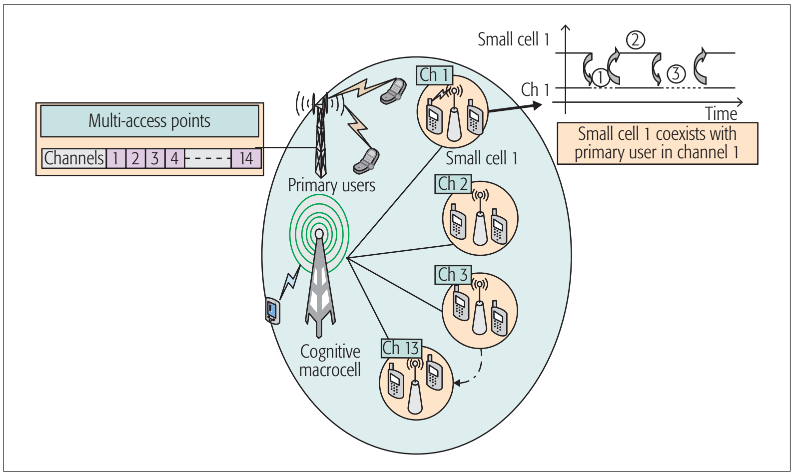

FIGURE 3. Time filling coexistence where each small cell is assigned to one of the IEEE 802.11 access points 5GHz band channels.

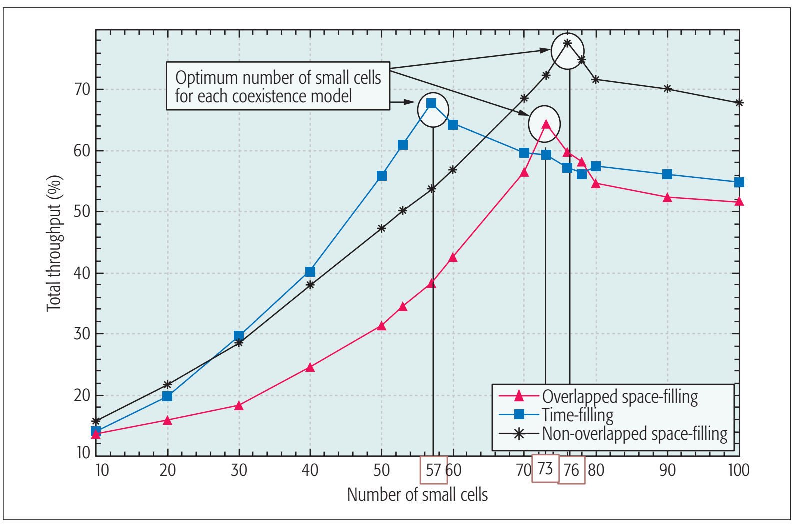

FIGURE 4. Total throughput vs. number of small cells.

Parameter	Value
Cell layout	*Sectors:* 1 macrocell, number of small cells, and 14 primary units
Users active per access point	2
Propagation model	Hata-large city
Number of available channels	14
Packet inter-arrival time	10 ms
Voice packet length	80 bytes
Application layer	
Encoder scheme	G.711 (silence)
Voice frames per packet	1
Type of service	Best effort (0)
Signaling	SIP
Max. ACK delay	0.2 sec
Max. ACK segments	2
Fast recovery	Reno
Cognitive radio network	
Physical characteristics	OFDM (802.11a)
Maximum transmission power	1 mW
Route request rate limit	10 pkts/sec
Node traversal time	0.04 sec
Primary network	
Physical characteristics	Direct sequence
Channel bandwidth	20 MHz
Max. receive lifetime	0.5 sec

TABLE 1. Simulation parameter values.

and network infrastructure, regardless of the used technology. This assumes that cognitive small cells will be able to trade off frequencies locally in a distributed mode without any engagement from operators' spectrum controllers. To summarize, small cells can be deployed anywhere on the network site to utilize the free transmission intervals that may become available in between primary network transmissions.

Performance Evaluation

System Setup

The OPNET simulation scenarios used in this work follow the same model as in [5]. In the simulated scenarios, each access point employs two end users. To simulate a dynamic spectrum model for cognitive communications, we assign one primary group (an access point and its associated users) to one of the 14 channels in the unlicensed 5 GHz band. These primary users can transmit at different time intervals, while leaving various lengths of time holes for the cognitive radio network. The dynamic spectrum holes at the primary network side were created by configuring the packet generation time and packet length relative to the overall simulation time. Also, small cells are given the opportunity to access the available free channels at free time holes. In our simulation configurations, we assign the same traffic load to all deployed nodes. In this way, traffic is scaled with the number of nodes that are deployed in each simulated scenario. Therefore, the number of small cells, in our results, reflects the traffic transferred in the network. The parameters of simulation are given in Table 1.

The simulation scenarios use the same global project attributes for traffic and channel availability to simulate the space filling and time filling schemes. While the number of small cells is increased in each scenario, the channel availability profile remains the same. The main goal of the simulated models is to analyze the threshold for the number of small cells that can be deployed at a macrocell site with predefined resources. Results are expected to help in developing a policy for future cognitive radio network planning.

Simulation Results

In the following, we report performance results as the number of small cells is increased in a cognitive small cell network. The overall throughput in Fig. 4 is increasing as the number of deployed small cells increases up to a certain number of small cells. The overall system performance starts to decline in terms of throughput percentage reduction as the number of small cells exceeds a specific number in the simulated model. The explanation for this is that small cells extend coverage area and spectrum access before reaching a threshold number of small cells at which point the deployed small cells exceed the free spectrum intervals available to the cognitive radio network. Once this happens, the cognitive small cells start to compete with each other, causing more interference and more backoffs for each other. The same performance is obtained for each of the simulated coexistence models. However, the non-overlapped space-filling scheme for cognitive small cell coexistence shows a higher number of hosted new small cells compared with other coexistence schemes. The overlapped space filling model shows the second highest number of small cells at 73 compared to the time filling model, which hosts only 57. However, the overall throughput achieved with the time filling model is slightly higher than the throughput obtained with the overlapped space filling model. This is because space filling enables more dynamic access to the spectrum pool, compared to the overlapped space filling model, allowing higher throughput with a lower number of small cells.

The end-to-end time delay in Fig. 5 is decreasing as the number of small cells increases up to a certain number of deployed cells. Bringing the access points near to end users as in ultra-dense small cell models reduces the time consumed for packet delivery, leading to reduced end-to-end delays. However, the time delay starts to increase again as the number of deployed small cells continues to increase, and especially when exceeding the available resources for cognitive communications, causing more packets to be buffered while waiting for delivery. Similar to Fig. 4, the non-overlapped space filling scheme for cognitive small cell coexistence hosts more small cells compared with time filling, even despite the fact that time filling coexistence has lower time delays.

The same performance can also be noticed in Fig. 6, which shows the total number of transmitted packets. The non-overlapped space filling scheme shows the highest percentage of transmitted packets, with 76 small cells deployed inside the macrocell area. The number of packets transmitted in the small cell network is increasing up to an optimal number of small cells. This means that the macrocell is the main access point that distributes the traffic to various cells even while dynamic changes occur in the network structure due to the deployment of new small cells. The optimum number can be reached once all the small cells share the non-overlapped space of the site area and have equal access to band channels. Exceeding the optimum number of small cells results in a significant decline in performance and a lower number of successfully transmitted packets, which occurs due to site partition complexity as the result of a large number of small cells. This also results in traffic congestion and rejected calls.

In summary, the overall number of deployed cognitive small cells is subject to the macrocell area size and the number of channels available by the cognitive macrocell. This study shows that there is a balance between the network structure and the resources offered to cognitive radio users regardless of the coexistence model used to integrate more small cells. Therefore, network planning engineers need to ensure the stability and continuity of a network structure employing ultra-dense small cells as an extension to the network coverage area or as a method for spatial slicing of spectrum. Further analysis in this area will significantly change the vision of the architectural design of 5G networks where ultra-dense small cells are anticipated to handle most of the network traffic.

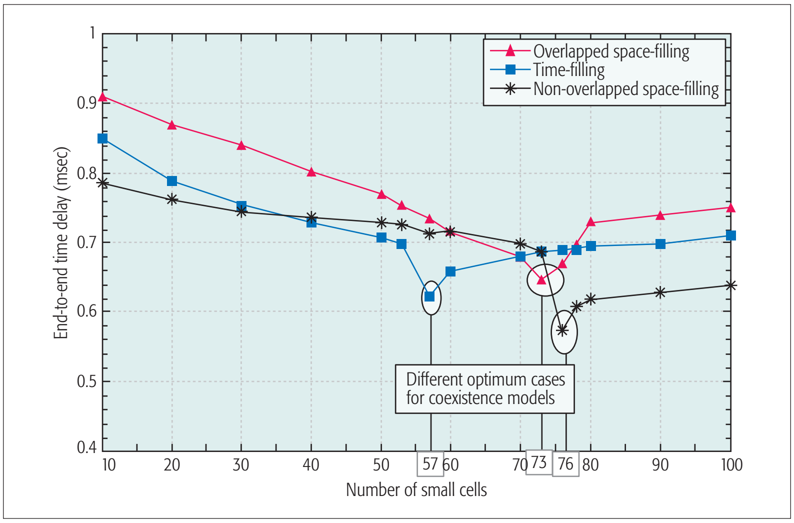

FIGURE 5. End-to-end time delay vs. number of small cells.

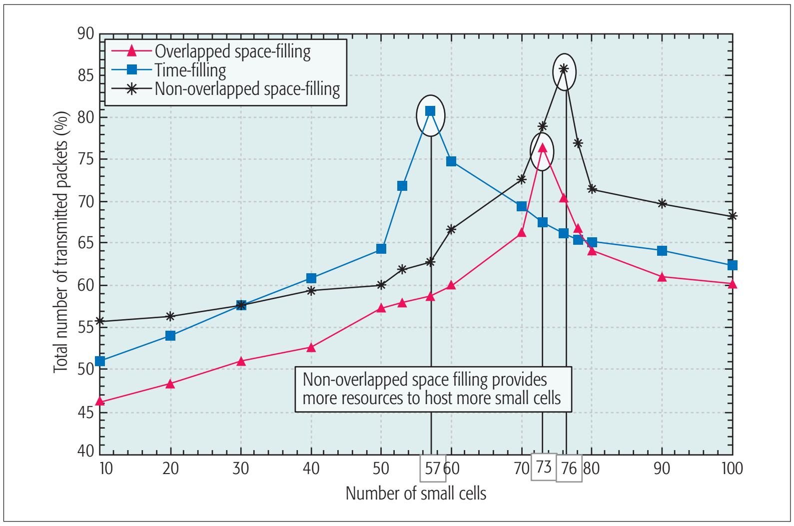

FIGURE 6. Total transmitted packets vs. number of small cells.

Conclusion

In this article, we have presented a cognitive small cell deployment scheme as a potential solution for efficient network planning and resource allocation in a dynamic wireless environment. This will be reflected in the design of future 5G communication systems with ultra-dense small cells. We considered spectrum coexistence techniques using two schemes: *Space Filling* where small cells can overlap their coverage areas; or just employ an advanced frequency reuse model without any overlapping, namely *Time Filling*. Finally, we showed system level analysis predicating performance at the optimum number of small cells that can be deployed in a cognitive macrocell domain. The ability to adapt regions of the cognitive radio network to cope with newly deployed small cells results in many network architectural breakthroughs, including optimal infrastructural design and utilizing the available spectrum.

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