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Review

In-Building Capacity Enhancement using Small Cells in Mobile Networks: An Overview

Rony Kumer Saha

Department of Electrical and Electronic Engineering, School of Engineering, BRAC University, 66 Mohakhali, Dhaka 1212, Bangladesh
E-mail: rony.saha@bracu.ac.bd

Abstract. In this paper, we give an overview of the state-of-the-art research studies to present the potential of small cells to address the high capacity demands of in-building users in mobile networks. In doing so, we discuss relevant theoretical backgrounds and carry out performance evaluations of key enabling technologies along with three major directions toward improving the network capacity, including spectrum accessibility, Spectral Efficiency (SE) improvement, and network densification. For the spectrum accessibility, numerous types of Small Cell Base Station (SBS) architectures of a Mobile Network Operator (MNO) are evaluated. For the SE improvement, cognitive radio techniques are evaluated for the Dynamic Spectrum Sharing (DSS) among multiple MNOs in a country. For the network densification, the spectrum reuse is evaluated at both intra-and inter-building levels for a given Co-Channel Interference (CCI) constraint. It is shown that multi-band multi-transceiver enabled small cells operating in the high-frequency millimeter-wave licensed or unlicensed spectrum to realize DSS techniques by exploiting SBS architectures for the spectrum accessibility, a hybrid interweave-underlay spectrum access in Cognitive Radio Networks for the spectral efficiency improvement, and both vertical and horizontal spectrum reuse in small cells deployed densely within buildings for the network densification can address high capacity demand in indoor mobile networks.

Keywords: 3D, small cell, network capacity, in-building, millimeter-wave, review, mobile network, cognitive radio, dynamic spectrum sharing.

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1. Introduction

1.1. Background

In typical cellular mobile networks, a major portion of the data is generated by indoor users at high data rates to support rich multimedia services on mobile phones, particularly in urban high-rise buildings, many of which encompass several hundreds of apartments. Due to the presence of high external wall penetration loss of a building, the scarcity of available system bandwidth below 3 GHz, and a limit to the maximum transmission power to avoid excessive interference, serving this large amount of indoor data at a high rate with an outdoor Macrocell Base Station (MBS) is difficult. Hence, it now becomes inevitable how to address indoor high data rates and enormous capacity demands.

In this regard, because of a small coverage and low transmission power, deploying Small Cell Base Stations (BSs) within buildings is considered an effective approach to serve such a large amount of indoor data at a high data rate. From Shannon's capacity formula, it can be observed that the network capacity can be improved mainly by addressing three directions, including spectrum accessibility, spectral efficiency improvement, and network densification.

Regarding spectrum accessibility, because spectrum bands below 3 GHz are almost occupied, the high-frequency Millimetre-Wave (mmWave) spectrum bands have already been considered to address the high capacity demand of Fifth-Generation (5G) and beyond mobile systems, particularly, indoors within multistory buildings. In this regard, to address the massive deployments of small cells to provide high data rates at a short distance, the short-range and the availability of a large amount of mmWave spectrum are promising, particularly in urban indoor environments. Further, the spectrum can be extended by increasing the number of available spectra such that each small cell can operate in more than one spectrum.

Besides, usually, each Mobile Network Operator (MNO) of a country is allocated a dedicated licensed spectrum to serve its users' traffic. Such static allocations of radio spectra were once sufficient to ensure user demands. To reuse the same dedicated spectrum for an MNO, recently, the dynamic sharing of radio spectrum allocated statically already to MNOs using small cells indoors is found more effective. In the Dynamic Spectrum Sharing (DSS), the spectrum allocated statically to a system (primary) can be shared dynamically or opportunistically by another system (secondary) subject to satisfying the condition that the primary system is not affected due to sharing. Indoor small cells, by exploiting their architectures, can play a crucial role in realizing numerous DSS techniques. In this regard, to avoid Co-Channel Interference (CCI), when sharing the licensed spectrum of one MNO with another, Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) can be employed in small cells to allow time orthogonality while serving traffic of the respective MNO.

Regarding spectral efficiency improvement, MNOs in a country facing challenges from enabling efficient utilization of its available licensed spectrum. This is because the user traffic demand of different MNOs in a country varies abruptly over time and space such that the demand for the required amount of spectra for different MNOs varies accordingly. This causes a great portion of the available spectrum allocated to each MNO in a country to be left unused or underutilized either in time or space. In recent times, Cognitive Radio (CR) has appeared as an enabling technology to address this spectrum under-utilization issue. In CR, spectrum access is a major function, which prevents collisions between the primary User Equipment (UE) and the Secondary UE to allow sharing of the licensed spectrum of one MNO with another to increase its effective spectrum bandwidth, resulting in improving its spectral efficiency to serve high capacity.

In addition, the radio environment in existing wireless networks is dynamic causing the signal to experience various unavoidable effects, including reflection, diffraction, scattering, and multipath fading which results in limiting the maximization of the spectral efficiency (SE) of wireless networks [1]. Moreover, the presence of high losses in high-frequency bands such as mmWave bands may not be overcome by novel optimization algorithms at the transmitter and receiver, resulting in further performance degradation. Intelligent reflecting surface (IRS) is a newer technology, which has the potential to overcome these poor channel propagation effects and hence increase signal coverage and reduce energy consumption at a lower deployment cost [2] by transforming the wireless channel from a highly probabilistic to a highly deterministic channel, allowing to achieve better SE and energy efficiency (EE) of 5G and beyond mobile networks [3].

An IRS, also known as a reconfigurable reflecting surface, large intelligent surface, and software-controlled meta-surface [3], is a meta-surface incorporating many small reconfigurable passive low-cost reflecting elements to introduce a controlled individual phase shift to the impinging electromagnetic wave. This in turn alters the propagation characteristic between the transmitter and receiver to maximize signal strength and mitigate interference [3]. In the presence of the line-of-sight (LOS) component, IRS enables the generation of a replica copy of the original LOS signal to improve the diversity of the system, while, in the absence of the LOS component, IRS establishes a virtual link between the transmitter and receiver causing the receiver to achieve the transmitted signal and hence to improve the overall SE. These cause the IRS a key technology for future wireless communications [2]-[3].

Furthermore, unlike Orthogonal Multiple Access (OMA) schemes, which are inherently inefficient due to limiting the number of users to be served simultaneously, another possible candidate to address the high spectral efficiency demands of the beyond 5G networks is to employ Non-Orthogonal Multiple Access (NOMA) techniques. More specifically, NOMA has recently been considered a key technology for Beyond 5G networks, where multiple users can access the same time and frequency resources at a time, resulting in increasing spectrum efficiency considerably [4]. There are mainly two NOMA schemes, including Code Domain NOMA (CD-NOMA) which assigns users unique spreading codes, and Power Domain NOMA (PD-NOMA) which operates by varying power levels of users to share time, frequency, or code slot simultaneously [4].

Finally, regarding network densification, Small Cell BSs (SBSs) can be deployed both on the intra-floor, as well as the inter-floor, level of a building, resulting in an ultra-dense deployment of SBSs over a certain area of 2-Dimensional (2D) physical space within the coverage of a macrocell. Moreover, due to the high penetration losses of mmWave bands through external and internal walls and floors in any multi-story building compared to low-frequency microwave bands, the reuse of mmWave bands can be explored in the third dimension (i.e., the height of a multistory building), which results in reusing the same mmWave band more than once at the inter-floor level. In addition, the conventional spectrum reuse techniques at the intra-floor level in a multistory building can be used to facilitate extensive reuse of mmWave spectra in ultra-dense deployed small cells within the building.

Hence, 3-Dimensional (3D) spatial reuse of mmWave spectra by capturing 3D effects on indoor signal propagations with in-building multiband-enabled ultra-dense small cells to avail additional spectrum using DSS, along with exploiting CR technology to improve spectrum utilization, can achieve enormous high capacity demand of mobile networks.

1.2. Related Work

Numerous existing research studies have already addressed the enabling technologies along with the three directions [5]-[17]. For example, Saha [5] and Saha and Aswakul [6] have addressed the modeling of in-building small cells in the mmWave and microwave spectrum bands, respectively. By deducing the minimum distance between co-channel small cells in both intra-floor and inter-floor levels subject to satisfying predefined interference thresholds, a 3D cluster of small cells has been defined such that the same spectrum can be reused in each 3D cluster of small cells within a building. It has been shown that both horizontal densification of small cells on each floor between adjacent buildings, as well as vertical densification of small cells between floors within each building, can achieve high capacity and SE indoors.

Further, Saha [7] has presented how to realize numerous in-building SBS architectures to enable numerous Dynamic Spectrum Sharing techniques by varying the number of physical transceivers as well as the number, amount, and characteristics of spectra per SBS. Further, using game theory, Kamal et al. [8] have presented inter-operator Dynamic Spectrum Access (DSA) algorithms. Furthermore, by allowing both operators to share a fraction of their licensed spectra, Joshi et al. [9] have presented DSS to improve their profit gain, as well as fairness.

Besides, the authors in [10]-[17] have addressed Cognitive Radio technology to address spectrum utilization. More specifically, Saha [10] has addressed an interweave spectrum access technique. Moreover, underlay spectrum access techniques by Saha [11], Khoshkholgh et al. [12], and Liang et al. [13], whereas hybrid interweave-underlay spectrum access techniques by Saha [14], Khan et al. [15], Zuo et al. [16], and Mehmeti et al. [17], have been addressed. It has been shown in [10]-[11], [14] that each spectrum access can improve the average capacity and SE when operating individually, and the hybrid interweave-underlay technique provides the best average capacity and SE performances of all [14].

Moreover, several existing works such as [3],[18]-[19] have already provided an extensive overview of IRS technology along with pointing out relevant open research issues and probable solutions. In particular, F. C. Okogbaa et al. [3] have provided a detailed survey of the IRS technology, limitations in existing research, and the related research prospects and probable solutions. Likewise, E. Basar et al. [18] have aimed to provide a detailed overview and historical perspective on state-of-the-art solutions and to elaborate on the fundamental differences with other technologies, important open research issues, and the reasons for introducing reconfigurable intelligent surfaces in wireless networks. Furthermore, M. D. Renzo et al. [19] have also provided an overview of the current research efforts on smart radio environments, the enabling technologies to realize them in reality, the need for new communication-theoretic models for their analysis and design, and the long-term and open research issues to be solved towards their massive deployment.

Similarly, extensive studies on NOMA techniques for Beyond 5G mobile networks have been ongoing. Specifically, A. Ahmed et al. [4] have employed a cooperative relaying scheme to improve the overall diversity gain and data rates of the NOMA system. In [20], B. Makki et al. have summarized the Third Generation Partnership Project (3GPP) discussions on NOMA and proposed several methods to reduce the implementation complexity and delay of both uplink and downlink NOMA-based transmission. Moreover, M. Vaezi et al. [21] have aimed at identifying numerous common myths about NOMA and clarifying why they are not true, along with posing critical questions important for the effective adoption of NOMA in 5G and beyond networks and identifying promising research directions for NOMA.

Hence, though studies in the context of in-building small cells that explore the above three directions of network capacity improvement are essential, no such study is not obvious in the existing literature.

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1.3. Contribution

In this paper, we address this gap by exploiting in-building small cells along these aforementioned three directions to achieve the high indoor capacity demand of existing and upcoming mobile networks. In doing so, we consider reviewing mainly the research works in [5]-[7], [10]-[11], [14]. Consequently, contents in this paper, in terms of texts, figures, equations, and other forms, can be found merged partly or fully with the above works. For interested readers, please refer to the relevant works for any sort of further information. References other than the above works are cited in the appropriate places, wherever used.

1.4. Organization

The paper is organized as follows. In Section 2, we first discuss the fundamentals of in-building small cells, including the main concept of small cell networks, small cell access mechanism, signal propagation characteristics within building environments, and suitable spectrum bands. Enabling technologies toward small cell network capacity improvement are discussed in Section 3. Spectrum accessibility is discussed under both direct and indirect approaches in Section 4. In Section 5, in-building network densification and spectrum reuse strategies are presented. Finally, section 6 covers spectral efficiency improvement techniques, particularly, interweave, underlay, and hybrid, spectrum access approaches. Performance results based on [5]-[7], [10]-[11], and [14] along three directions toward achieving high in-building capacity are evaluated in Section 7. We conclude the paper in Section 8. A list of abbreviations is given in Table 1.

2. Fundamentals of In-Building Small Cells

2.1. Small Cells

A small cell can be defined as a cellular radio access node that provides small coverage (typically in the order of 10 meters) at low power (e.g., 20-23 dBm) in both licensed and unlicensed spectrum bands to serve its users' mobile and Internet services. Small cells can be used to provide in-building and outdoor wireless coverage at high capacity and data rate within a short distance. Femtocells are examples of small cells. Small cells can be deployed by users or network operators. Operators use them to extend their networks, particularly, to cover dense urban areas, where the presence of several high-rise buildings is a usual scenario, to provide a good signal quality. Note that, in this paper, we limit the discussion to the use of small cells under in-building scenarios (Fig. 1). Also, we use the terms "small cell" and "femtocell" interchangeably.

Table 1. A list of abbreviations.

Abbreviation	Description
2D	2-Dimensional
3D	3-Dimensional
4G	Fourth-Generation
5G	Fifth-Generation
ABS	Almost Blank Subframe
APP	ABS Pattern Period
BS	Base Station
CCI	Co-Channel Interference
CR	Cognitive Radio
CSA	Co-channel Shared Access
cSBS	Co-channel SBS
DSS	Dynamic Spectrum Sharing
EE	Energy Efficiency
eICIC	Enhanced Intercell Interference Coordination
hRF	Horizontal Reuse Factor
LAA	Licensed Assisted Access
LOS	Line-of-Sight
LSA	Licensed Shared Access
MBS	Macrocell Base Station
mmWave	Millimeter-Wave
MNO	Mobile Network Operator
p-MNO	Primary MNO
PU	Primary UE
RoE	Region of Exclusion
SBS	Small Cell Base Station
SE	Spectral Efficiency
SINR	Signal-to-Interference-plus-Noise-Ratio
SLSA	Static Licensed Spectrum Allocation
s-MNO	Secondary MNO
sSBS	Serving SBS
sSU	Serving Small Cell UE
SU	Secondary UE
TTI	Transmission Time Interval
UE	User Equipment
vRF	Vertical Reuse Factor

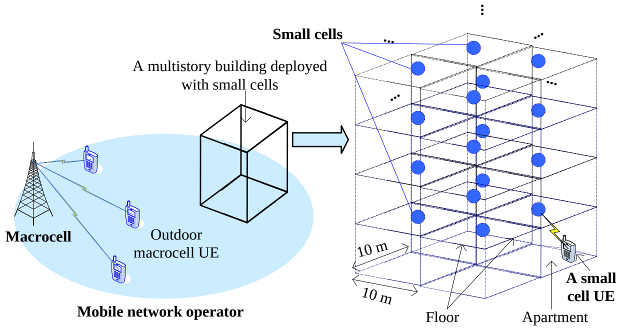


Fig. 1. In-building small cell networks.

2.2. Small Cell Access Mechanism

Femtocells are considered small cells, and there are mainly three approaches to access a small cell, i.e. femtocell, as follows. In closed access, only a specific number of users registered (typically, home users) can get access to a femtocell (Fig. 2). In open access, an arbitrary number of users of the cellular operator nearer to a femtocell (however, far away from the macrocell) can access the corresponding femtocell. However, when some of the resources are reserved for the registered home users and the rest is assured for other users, such a deployment approach is called hybrid access.

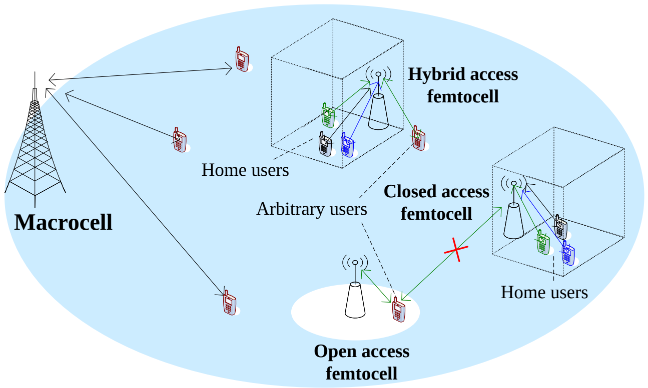


Fig. 2. Approaches to access a small cell (i.e., femtocell).

Hence, closed access is well suited to home users to keep the network private, as well as to secure sufficient capacity to serve traffic. Likewise, Open access is suitable for the network owner due to extending its coverage. However, to avoid starving from accessing resources in open access, whereas to limit interference generated in the uplink by closed access, operators prefer hybrid access. Finally, the distance of a user from the macrocell defines the choice of the deployment of femtocells, be it open, closed, or hybrid access.

2.3. In-building Signal Propagation Characteristics

2.3.1. Path Loss and Multi-path Fading

In high frequencies, the path loss indoors is frequency-dependent. For example, the path loss in the 28 GHz for omnidirectional radiation pattern can be expressed as follows.

$$PL[\mathrm{dB}] = 10\log_{10}\left(4\Pi d_0 f_c/c\right)^2 + 10n\left(1+b\left(f - f_0/f_0\right)\right)\log_{10}\left(d/d_0\right) + X_\Delta \quad (1)$$

where *n* denotes path loss exponent, *b* represents the slope of linear frequency dependence of path loss, f_0 represents a fixed reference frequency serving as the balancing point of the linear frequency dependence of *n*. X_Δ is the Gaussian random variable with standard deviation. Λ represents large-scale signal variation about the mean path loss due to shadowing.

In indoor environments, there is a high possibility of the existence of line-of-sight components between a UE and a BS. The indoor channel within the same local area is grossly similar as the channel's structure does not change considerably over short distances. For a similar structure of all apartments within a multi-floor building, all indoor channels can be assumed to experience a similar shadowing effect. Further, the small-scale channel fading occurs due to Doppler spread and delay spread effects on the channel.

However, due to the relatively low mobility of UEs and objects between a UE and BS, an indoor channel between a UE and BS experiences a less Doppler spread as compared with an outdoor channel which results in a large channel coherence time. Further, an indoor channel observes a less delay spread, mostly less than 100 ns. So, because of less delay and Doppler spreads of indoor channels, indoor channel characteristics are less susceptible to small-scale fading effects and do not change significantly within the same location area. Hence, indoor channels within a building can be considered to experience approximately the same overall large-scale and small-scale fading effects.

2.3.2. Penetration Loss

Floor penetration loss is frequency-dependent and increases rapidly with an increase in frequency. Floor penetration loss is not fixed for all floors between transmitters and receivers. Instead, the impact of floor penetration loss is nonlinear, whereby it decreases with an increase in the number of floors. No standard methodology has yet been developed to measure the penetration loss of walls and floors for different building materials [4]. Using [22] and fitting the curve for a concrete block in [23], according to [5], the floor penetration loss in the 28 GHz mmWave spectrum is 55 dB for the first floor (Table 2).

Moreover, internal and external wall penetration losses play a significant role. Table 2 shows penetration losses for the 28 GHz of both internal and external walls. This large penetration loss (at high frequencies, e.g. at 28 GHz) for both intra-floor (due to internal walls) and inter-floor levels, along with high external wall penetration loss, causes the radio frequency to be confined within a building, resulting in no or insignificant interference with outdoor signals of the same frequency.

Also, the strength of an outdoor signal when penetrating through an external wall of a building becomes poor, resulting in reusing the frequency of an outdoor base station to indoor users served by indoor base stations within the building [24]. When reusing the frequency of an outdoor base station to indoor users, the presence of outdoor users within the same building as that of indoor users causes significant co-channel interference with indoor users, which needs proper interference management. Note that as the frequency increases, the penetration losses increase accordingly.

Table 2. Floor penetration loss in the 28 GHz mmWave spectrum band [22]-[23] [25]-[26].

Obstacle	Penetration loss (dB)
Floor (reinforced concrete)	55
Internal wall	6.84
External wall (brick)	28

2.3.3. Indoor Propagation Modeling

Two major approaches that can be considered for modeling signal propagation in-building scenarios:

- *Approach 01*: When considering nearby buildings' reflection effects, particularly in urban environments where buildings are very close in distance to one another;
- *Approach 02*: When no nearby buildings' reflection effects are considered such that an isolated building is concerned, and only in-building propagation of signals through floors, reflected signals from walls, ceilings, and floors, and diffracted signals from the edges of building through windows are to be considered.

Approach 02 is simpler and is a valid assumption when both the transmitter and receiver are located inside a building such that there is sufficient building attenuation to make the effect of surroundings insignificant.

2.4. Suitable Spectrum Bands

MmWave bands offer a large amount of bandwidth that can address the scarcity of radio spectrum. A major feature of mmWave systems is the dominance of the LOS components in the propagating signals because of the quasi-optical propagation characteristics. Moreover, the mmWave spectrum can allow service providers to expand the channel bandwidth beyond 20 MHz used in the Fourth-Generation (4G) systems, which results in supporting the increased data rates.

Due to the high external wall penetration loss of a building, mmWave signals cannot penetrate easily, resulting in isolating indoor networks from those outdoors. Such isolations allow reusing the same outdoor mmWave spectrum indoors with an insignificant co-channel interference effect, resulting in an improved mmWave spectrum capacity and spectrum efficiency. Furthermore, because of the very small wavelengths and advances in low-power Complementary Metal-Oxide-Semiconductor (CMOS) radio-frequency circuits, a large number of miniaturized antennas can be placed in small areas of less than 1 or 2 cm^2 to achieve very high gain, which can be either fabricated at the BS or in the skin of a mobile device to provide path diversity from the blockage by human obstructions [27]-[28].

3. Enabling Technologies Toward Small Network Capacity Improvement

The received signal capacity at a receiver is a function of the distance from the transmitter and available spectrum bandwidth. The lower the distance and higher the spectrum bandwidth, the better the received signal capacity. The distance can be lowered by reducing the cell size so that the transmitter and receiver are as close in distance as possible. Figure 3 shows the formation of small cells each having a radius *r* operating at the spectrum bandwidth of *b* from a large macrocell having a radius *R* operating at the spectrum bandwidth of *B*.

Clearly, it can be observed that the reduction in the macrocell coverage into several smaller ones allows reusing the same spectrum (*B* where *B*=*b*) spatially (an indirect impact toward the spectrum extension), resulting in achieving more capacity over a certain area (i.e., $C_S = x \times C_M$ where C_M and C_S denote, respectively, the macrocell capacity and the total small cell capacity, and x denotes spectrum reuse factor, which is 7 in Fig. 3), assuming that the Signal-to-Interference-plus-Noise-Ratio (SINR) is the same for both the macrocell and small cells.

From Shannon's capacity formula given in Eq. (2), it can be observed that the network capacity can be improved mainly by addressing three directions, including spectrum accessibility, spectral efficiency improvement, and network densification.

$$C_L = \Phi \times B\,\mathrm{Log}_2\left(1+\left(\frac{P_r}{N+I_T}\right)\right) \qquad (2)$$

where C_L, Φ, B, P_r, N, and I_T denote, respectively, achievable capacity, spectrum reuse factor, available spectrum bandwidth, received desired signal power, noise, and received total interference signal power.

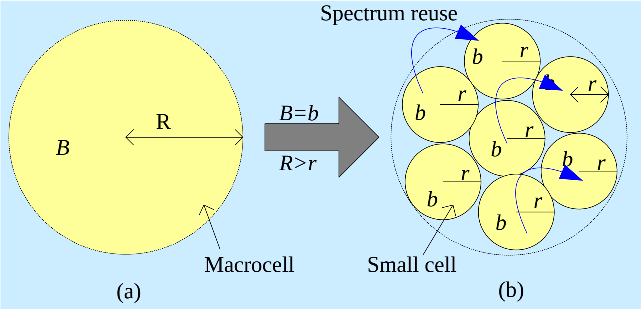


Fig. 3. Formation of small cells from a large macrocell. (a) A macrocell, (b) A set of small cells.

These are shown in a network capacity improvement triangle in Fig. 4 along with three directions. Corresponding enabling technologies to improve network capacity indoors using small cells deployed in a building are also shown in each direction and discussed in brief in what follows.

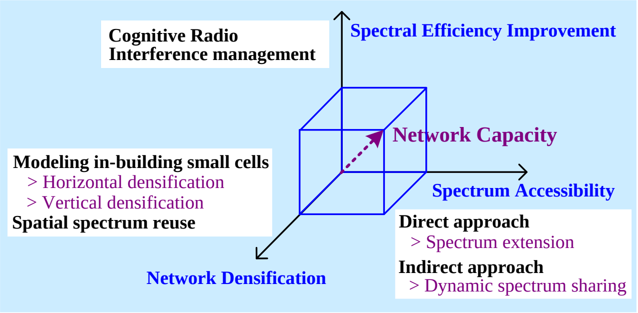


Fig. 4. Network capacity improvement triangle.

3.1. In-Building Small Cell Network Densification

Because of a small coverage and low transmission power, deploying SBSs within buildings is considered an effective approach to serve such a large amount of indoor data at a high data rate. Besides, SBSs can be deployed both on the intra-floor, as well as the inter-floor, level of a building, resulting in an ultra-dense deployment of SBSs over a certain area of 2D physical space within the coverage of a macrocell. This necessitates capturing 3D effects, e.g. floor penetration loss, on indoor signal propagations by considering the height of a building.

3.2. 3D Spatial Spectrum Reuse Indoors

Due to the high penetration losses of mmWave bands through external and internal walls and floors in any multi-story building compared to low-frequency microwave bands, the reuse of mmWave bands can be explored in the third dimension (i.e., the height of a multistory building), which results in reusing the same mmWave band more than once at the inter-floor level. In addition, the conventional spectrum reuse techniques at the intra-floor level in a multistory building can be used to facilitate extensive reuse of mmWave spectra in ultra-dense deployed small cells within the building.

Importantly, the capacity is directly proportional to the available spectrum bandwidth of a channel, which can be extended by increasing, for example, the number of available spectra, such that each small cell can operate in more than one spectrum and the number of times the same spectrum is reused by small cells through vertical spatial reuse in a multistory building. Hence, techniques for 3D spatial reuse of high-frequency mmWave spectra with in-building multiband-enabled small cells can achieve enormous high capacity and data rates per user demands expected for the future mobile networks.

3.3. Spectrum Extension in Millimeter-Wave Bands

The mmWave spectrum bands are considered promising candidate bands for the spectrum extension to address the high capacity demand of next-generation mobile systems such as 5G and beyond systems in dense urban multistory buildings. Besides, MNOs continue to reduce cell coverage to exploit spatial reuse. In this regard, to address the massive deployments of small cells to provide high data rates at a short distance, the short-range (typically, 100-200 m in radius) mmWave technologies are considered promising, particularly in urban indoor environments. Furthermore, because of the availability of a large amount of the mmWave spectrum, a single MNO may not be able to utilize the mmWave spectrum fully. In such cases, sharing the mmWave spectrum dynamically among multiple operators in a country can contribute to improving further the utilization of the mmWave spectrum.

3.4. Dynamic Spectrum Sharing and Interference Management

Besides, usually, each MNO of a country is allocated with a dedicated licensed spectrum to serve its users' traffic. Such static allocations of radio spectra were once sufficient to ensure user demands. To reuse the same dedicated spectrum for an MNO, techniques such as fractional frequency reuse are useful to serve more users with reasonable data rate demands. In the last decade, the demand for mobile communications has grown significantly due to an increase in the number of subscribers as well as the volume of traffic and data rate per user. Since the major portion of data is generated in indoor environments, ensuring high indoor data rates and capacity per user have become crucial demands. Even though the subscriber base of an MNO has increased tremendously, the radio spectrum allocated to an MNO has not been increased proportionately. Recently, the dynamic sharing of radio spectrum allocated statically already to MNOs using small cells indoors is found to be more effective.

In the DSS, the spectrum allocated statically to a system (primary) can be shared dynamically or opportunistically by another system (secondary) subject to satisfying the condition that the primary system is not affected due to sharing. Indoor small cells, by exploiting their architectures, can play a crucial role in realizing numerous DSS techniques. In this regard, to avoid CCI, when sharing the licensed spectrum of one MNO with another, the ABS-based eICIC can be employed in small cells to allow time orthogonality while serving the traffic of the respective MNO.

3.5. Cognitive Radio

Another major challenge for an MNO in a country is to enable efficient utilization of its available licensed spectrum. This is because the user traffic demand of different MNOs in a country varies abruptly over time and space such that the demand for the required amount of spectra for different MNOs varies accordingly. This causes a great portion of the available spectrum allocated to each MNO in a country to be left unused or underutilized either in time or space. In this regard, since most data is generated indoors, particularly in dense urban multistory buildings, serving a large volume of data at high rates indoors causes these above challenges even more critical.

Hence, increasing the available spectrum of an MNO on one hand and improving the utilization of its spectrum, on the other hand, is crucial to maximizing serving its increased user demand at high data rates, particularly in dense urban multistory buildings. In recent times, CR has appeared as an enabling technology to address this spectrum under-utilization issue. In CR, spectrum access is a major function, which prevents collisions between Primary UEs (PUs) and Secondary UEs (SUs) to allow sharing of the licensed spectrum of one MNO with another to increase its effective spectrum bandwidth to serve high data rates and capacity.

Each of the three directions in the network capacity improvement triangle shown in Fig. 4 (i.e., spectrum accessibility, spectrum efficiency improvement, and network densification) by employing the corresponding enabling technologies described above towards improving the in-building capacity is detailed in the following sections.

4. Spectrum Accessibility

Because spectrum bands below 3 GHz are almost occupied, the high-frequency mmWave spectrum bands have already been considered to address the high capacity demand of 5G and beyond mobile systems, particularly, indoors within multistory buildings. In this regard, to address the massive deployments of small cells to provide high data rates at a short distance, the short-range and the availability of a large amount of mmWave spectrum are promising, particularly in urban indoor environments. The available spectrum for an MNO can be increased in two major ways as follows:

- Direct approach: by adding (licensing) new spectrum statically and
- Indirect approach: by sharing used spectrum dynamically/ opportunistically.

In the direct approach, a new licensed spectrum can be added directly to a mobile system using techniques such as carrier aggregation (Fig. 5), be it contiguous or noncontiguous. However, the traditional direct approaches to extending the spectrum are no more effective due to the scarcity of radio spectrum availability, particularly below 3 GHz [29], as well as the huge cost of licensing spectrum. This asks for exploiting indirect approaches to address ever-increasing indoor high data rates and capacity demands for MNOs.

In the indirect approach, the spectrum already used by a system (primary) can be shared dynamically or opportunistically by another system (secondary) subject to satisfying the condition that the primary system is not affected due to sharing. Such an approach can be termed DSS. Small cells indoors can play a crucial role in DSS.

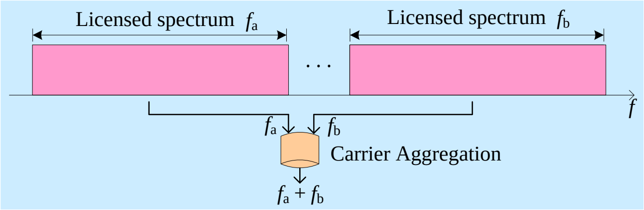


Fig. 5. Spectrum access using the carrier aggregation approach.

Based on the number of physical transceivers as well as the number, amount, and characteristics of operating spectra of an SBS, several small cell base station architectures can be realized to address numerous DSS approaches [7]. More specifically, in [7], by enabling SBSs with a single-/multiple-transceiver and operating them at either a single or multiple licensed/unlicensed spectra of homogeneous/ heterogeneous systems, nine types of SBS architectures are exploited to realize numerous DSS approaches, including Co-Channel Shared Access (CSA), Licensed Shared Access (LSA), Unlicensed Shared Access (ULA), Authorized Shared Access (ASA), Co-primary Shared Access (CoPSA), and Licensed Assisted Access (LAA), which are described in brief as follows.

Like [7], Let xm denotes the maximum number of MNOs such that $x \in \boldsymbol{x} = \{1, 2, ..., \mathrm{xm}\}$ denotes a set of MNOs assigned with the licensed spectra $f_x \in \boldsymbol{f_x} = \{f_1, f_2, ..., f_{\mathrm{xm}}\}$. Let $F_{l,x} \in \boldsymbol{F_{l,x}} = \{F_{l,1}, F_{l,2}, ..., F_{l,\mathrm{xm}}\}$ denote a set of licensed spectrums of other systems than any mobile system, e.g. satellite systems and Fixed Wireless Access (FWA). Also, let $F_{ul,x} \in \boldsymbol{F_{ul,x}} = \{F_{ul,1}, F_{ul,2}, ..., F_{ul,\mathrm{xm}}\}$ denote a set of unlicensed spectrums, e.g. 60 GHz, 5 GHz, and 2.4 GHz, and f_2 denotes the spectrum of the MBS.

- *Type 1 - single-transceiver single-band enabled SBSs operating in the licensed spectrums of homogeneous systems* (Fig. 6): In this type of SBS, both the MBS and an SBS operate on their own MNO's spectrum subject to the interference management policy set by the MNO. This Type of SBS can be used for the CSA between an MBS and in-building SBSs of an MNO using the eICIC technique.

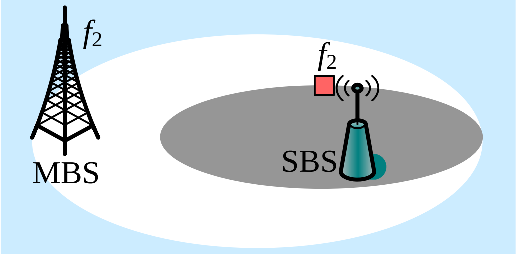


Fig. 6. Type 1 SBS architecture.

- *Type 02 - single-transceiver single-band enabled SBSs operating in the licensed spectrums of heterogeneous systems* (Fig. 7): The MBS and an in-building SBS of an MNO operate at different frequencies. This Type of SBS can be used for the LSA for sharing the licensed spectrum of a heterogeneous system with in-building SBSs of an MNO.

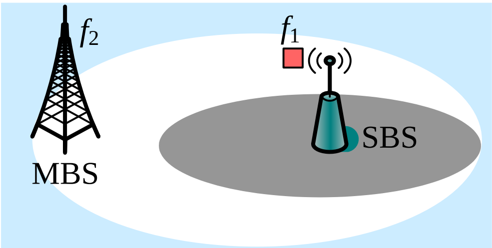


Fig. 7. Type 2 SBS architecture.

- *Type 03 - single-transceiver single-band enabled SBSs operating in the unlicensed spectrums of heterogeneous systems* (Fig. 8): In-building SBSs of an MNO operate in an unlicensed heterogeneous spectrum band. This Type of SBS can be used for the ULA to operate in-building SBSs of an MNO at an unlicensed heterogeneous spectrum band.

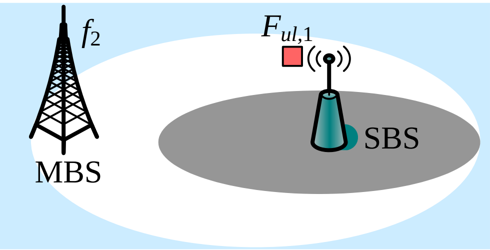


Fig. 8. Type 3 SBS architecture.

- *Type 04 - single-transceiver multiband enabled SBSs operating in the licensed spectrums of homogeneous systems* (Fig. 9): An in-building SBS operates in the spectrum of multiple MNOs in the same region using a single-transceiver by employing techniques such as carrier aggregation. The ASA can be realized subject to interference management among MNOs.

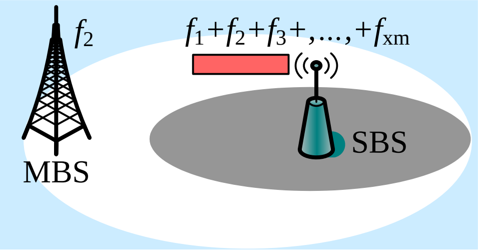


Fig. 9. Type 4 SBS architecture.

- *Type 05 - multi-transceiver multiband enabled SBSs operating in the licensed spectrums of homogeneous systems* (Fig. 10): Multiple transceivers are needed due to the diverse signal propagation characteristics at the operating spectrums of MNOs. The CoPSA such as spectrum pooling and spectrum renting can be realized.

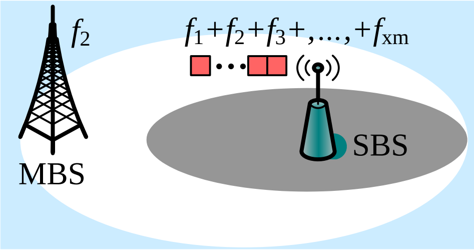


Fig. 10. Type 5 SBS architecture.

- *Type 06 - multi-transceiver multiband enabled SBSs operating in the licensed spectrums of heterogeneous systems* (Fig. 11): An in-building SBS operates at the spectrums of its own MNO as well as a heterogeneous system (e.g., a satellite system) using multiple transceivers. The CSA can be realized with one transceiver and the LSA can be realized with another transceiver of the SBS.

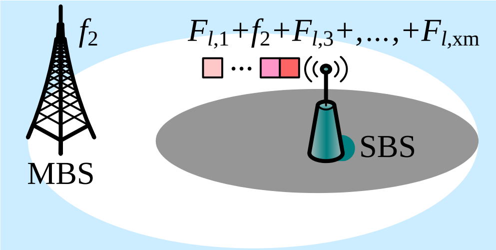


Fig. 11. Type 6 SBS architecture.

- *Type 07 - multi-transceiver multiband enabled SBSs operating in the unlicensed spectrums of heterogeneous systems* (Fig. 12): An SBS operates at the spectrum of its own MNO as well as at the unlicensed spectrum of a heterogeneous system using multiple transceivers. The CSA can be realized with one transceiver and the LAA can be realized with another transceiver of the SBS.

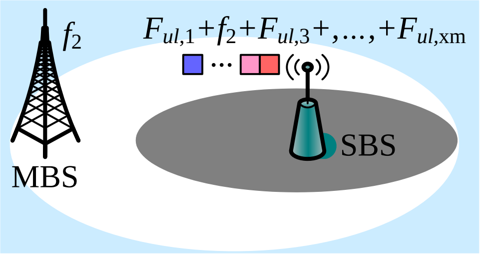


Fig. 12. Type 7 SBS architecture.

- *Type 08 - multi-transceiver multiband enabled SBSs operating in the licensed and unlicensed spectrums of heterogeneous systems (option 1)* (Fig. 13): One of the transceivers of an SBS operates at the licensed spectrum of a heterogeneous system (e.g., a satellite system) and the other transceiver operates at an unlicensed spectrum (i.e., 60 GHz unlicensed spectrum) using dual transceivers. LSA can be realized with one transceiver, whereas LAA with another transceiver.

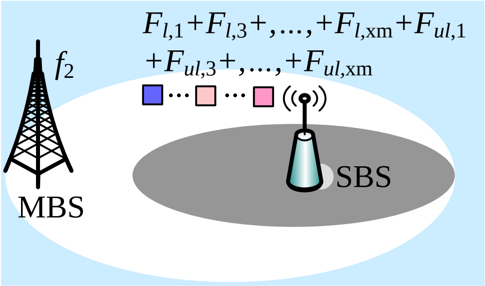


Fig. 13. Type 8 SBS architecture.

- *Type 09 - multi-transceiver multiband enabled SBSs operating in the licensed and unlicensed spectrums (option 2)* (Fig. 14): One of the transceivers of an SBS operates at the spectrum of its own MNO, and the second transceiver operates at the licensed spectrum of a heterogeneous system (e.g., a satellite system), and the third transceiver operates at an unlicensed spectrum (e.g., 60 GHz unlicensed spectrum) using multiple transceivers. Transceiver 1 of an SBS and the spectrum of the MBS of its MNO can realize CSA, transceivers 1 and 2 of the SBS can realize LSA, and transceivers 1 and 3 of the SBS can realize LAA. All the realized DSS approaches by exploiting an SBS architecture are shown in Table 3.

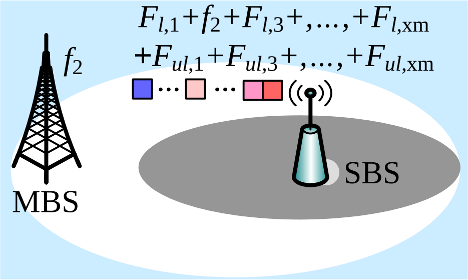


Fig. 14. Type 9 SBS architecture.

Table 3. Realized spectrum sharing accesses using the proposed types of in-building sbs architectures.

SBS architecture	DSS
Type 1	CSA
Type 2	LSA
Type 3	ULA
Type 4	ASA
Type 5	CoPSA
Type 6	CSA and LSA
Type 7	CSA and LAA
Type 8	LSA and LAA
Type 9	CSA, LSA, and LAA

To avoid CCI when sharing the licensed spectrum of a homogeneous/heterogeneous system, the ABS-based eICIC technique is applied to any transceiver of an SBS depending on its operating spectrum. The eICIC technique is based on the following principle: “An SBS architecture can be configured such that it can operate only during non-ABSs per ABS Pattern Period (APP)” as shown in Fig. 15. An ABS is a Transmission Time Interval (TTI) during which no data signal is transmitted except for some control signals

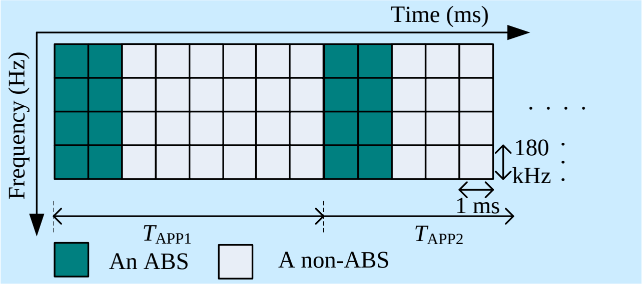


Fig. 15. An illustration of the ABS-based eICIC technique [7]. T_{APP1} and T_{APP2} denote APP 1 and APP 2, respectively.

such as broadcast and synchronization signals. An SBS can be scheduled at the same frequency as that of another system only during non-ABSs per APP [7]. Note that for an unlicensed band, no CCI is considered.

5. Network Densification

SBSs can be deployed both on the intra-floor, as well as the inter-floor, level of a building, resulting in an ultra-dense deployment of SBSs over a certain area of 2D physical space within the coverage of a macrocell. Moreover, due to the penetration losses of external and internal walls, as well as floors, in any multi-story building, the reuse of the same spectrum can be explored in both the intra-floor, as well as the inter-floor, levels of the building. This results in reusing the same spectrum more than once in small cells within a building, which we discuss in the following adoption [6].

Consider a 3D multi-floor building that consists of several 2D floors, and each floor consists of a number of square-grid apartments with each side length of a=10m. A cluster of SBSs is deployed in apartments of the building such that each apartment has one SBS [6]. We assume that all SBSs are located on the ceilings and centers of all apartments. Figure 16 shows intra-floor CCI modeling. The region up to which the aggregate interference is significant enough so that it exceeds a maximum allowable aggregate interference at a serving UE (sUE) is termed the Region of Exclusion (RoE) for reusing the same spectrum resources of a serving SBS (sSBS) in any SBSs within the RoE.

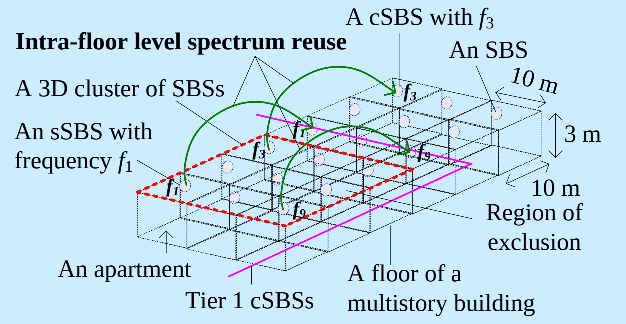


Fig. 16. Intra-floor CCI and RoE modeling [28].

Since intra-floor interference modeling addresses CCI effect within a floor, and there exists an additional high floor attenuation loss between sSU and a cSBS, it is not necessary to take into account of CCI effect from all cSBSs on co-channel interferer floors except those two cSBSs located on either a vertically straight up or down floors from the serving floor of sSBS. We define a serving floor as the one where sSBS is located, and an interferer floor as the one where any cSBSs of sSBS is located [6]. With this concern, inter-floor interference modeling can be performed as shown in Fig. 17.

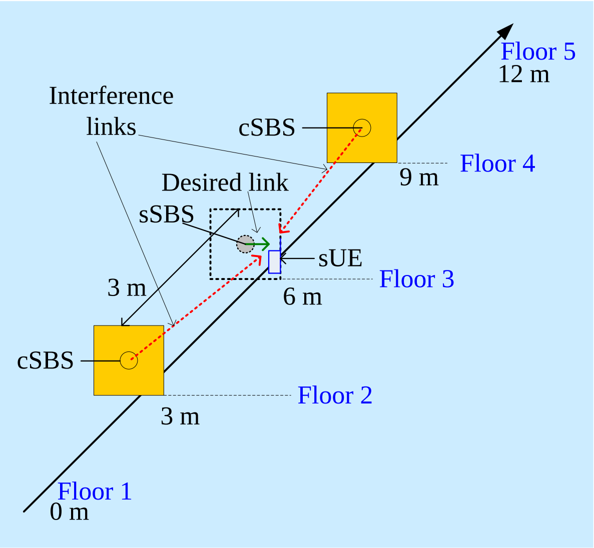


Fig. 17. Inter-floor interference modeling and architecture [6].

Figure 18 shows 3D in-building small cell interference modeling that combines the effects of intra-floor and inter-floor CCIs [6]. If the reuse of resources is performed on an intermediate floor, two cSBSs need to be considered, one is located on a bottom floor, and the other is on an up floor from the serving floor so long as both cSBSs exist on both sides of the serving floor. However, if the serving floor is either the top or bottom most of all floors, the number of cSBSs is only one since there is at most one cSBS located respectively on either a bottom or an up floor from the serving floor.

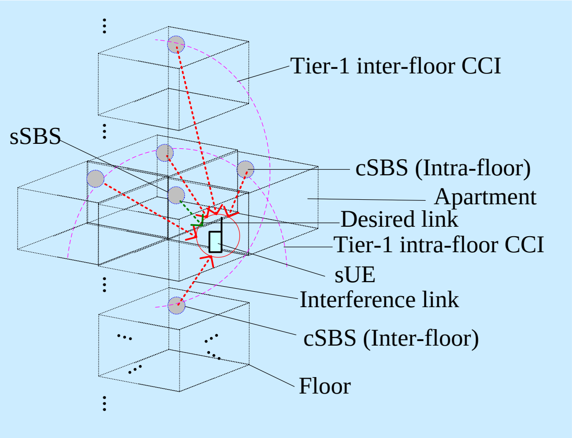


Fig. 18. A detailed 3D in-building intra-and inter-floor interferences model and architecture for reusing resources in SBSs [30].

The normalized value of intra-floor interference power at an arbitrary distance d_{tra} from a cSBS at sSU is given by [6],

$$\alpha_{tra}\left(d_{tra}\right)=\left(d_{\min}/d_{tra}\right)^{3} \tag{3}$$

Likewise, the normalized value of inter-floor interference power for an arbitrary distance d_{ter} from a cSBS located on a floor other than that of sSBS at sSU is given by [6],

$$\alpha_{ter}\left(d_{ter}\right)=10^{-\left(0.1\alpha_{f}\left(d_{ter}\right)\right)}\left(d_{\min}/d_{ter}\right)^{3} \tag{4}$$

where $\alpha_f(d_{ter})$ denotes floor attenuation factor.

In a 3D multi-floor building, since cSBSs are present in both intra-floor and inter-floor levels as shown in Fig. 18, the total aggregate interference power at sSU is given by,

$$\alpha_{agg,tot}=\alpha_{agg,ter}+\alpha_{agg,tra} \tag{5}$$

where $\alpha_{agg,tra}$ and $\alpha_{agg,ter}$ denote respectively an aggregate interference power of intra-floor and inter-floor cSBSs received at sFU.

Let $\alpha_{thr,tra}$, $\alpha_{thr,ter}$, and $\alpha_{thr,tot}$, respectively, denote intra-floor interference, inter-floor interference, and total interference power constraints at sFU. If $\alpha_{agg,ter}\leq\alpha_{thr,ter}$ and $\alpha_{agg,tra}\leq\alpha_{thr,tra}$, then $\alpha_{agg,ter}+\alpha_{agg,tra}\leq\alpha_{thr,ter}+\alpha_{thr,tra}$. A minimal separation distance d^{*}_{tra} for intra-floor level and d^{*}_{ter} for inter-floor-level can be expressed as follows [6]

$$d^{*}_{tra}\geq d_{\min}\left(y_{\max,tra}/\alpha_{thr,tra}\right)^{1/3} \tag{6}$$

$$d^{*}_{ter}\geq d_{\min}\left(10^{-\left(\alpha_{f}\left(d^{*}_{ter}\right)/10\right)}\left(y_{\max,ter}/\alpha_{thr,ter}\right)\right)^{1/3} \tag{7}$$

where $y_{\max,ter}=1$ for single-sided cSBSs, and $y_{\max,ter}=2$ for double-sided cSBSs. Also, $y_{\max,tra}=8$.

Let $\mathcal{S}_{\text{tra}}$ and $\mathcal{S}_{\text{ter}}$ denote, respectively, the number of SBSs in clusters of intra-floor and inter-floor levels corresponding to the minimum separation distance d^{*}_{tra} for intra-floor level and d^{*}_{ter} for inter-floor-level. Then, the size of a 3D cluster of SBSs is given by [6], $\mathcal{S}_{\text{3D}}=\mathcal{S}_{\text{tra}}\times\mathcal{S}_{\text{ter}}$ such that the same spectrum bandwidth can be reused in each cluster of SBSs. Figure 19 shows an example minimum distance constraint-based 3D cluster of SBSs with respect to floor n+1. RoEs for both intra-and inter-floor levels are shown with red color lines. Green color circles represent cSBSs and ash color circles represent non-cSBSs. Hence, resources can be reused in every 3 SBSs intra-floor level and every alternate floor inter-floor level such that a 3D cluster consists of 18 SBSs [6].

The minimum distances are frequency-dependent since the distant-dependent path loss in indoor environments is frequency-dependent. Hence, they vary with the change in carrier frequencies. These correspondingly vary the 3D cluster size and hence the spectrum reuse factor within a 3D building. Note that the above expressions for the minimum distances correspond to low-frequency below 3 GHz carrier.

For a different carrier frequency, e.g. 28 GHz, the above expressions become as follows [5].

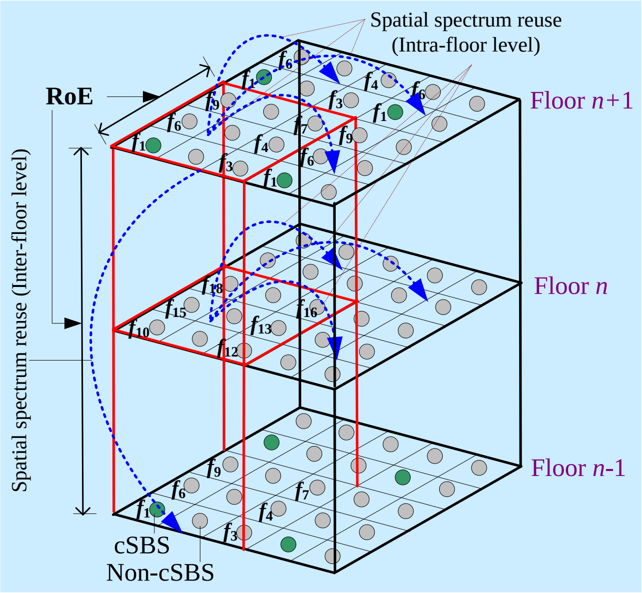


Fig. 19. Formation of an in-building 3D cluster of SBSs subject to satisfying the minimum distance constraints in both intra-and inter-floor levels to reuse the same spectrum in a 3D in-building scenario [6].

$$d^*_{tra} \geq d_{\min}\left(y_{\max,tra}/\alpha_{thr,tra}\right)^{1/1.797} \quad (8)$$

$$d^*_{ter} \geq d_{\min}\left(10^{-\left(\alpha_f\left(d^*_{ter}\right)/10\right)}\left(y_{\max,ter}/\alpha_{thr,ter}\right)\right)^{1/1.797} \quad (9)$$

In general, an increase in carrier frequency causes to decrease in cluster size such that the same spectrum can be reused more for the same building of SBSs.

6. Spectral Efficiency Improvement

The scarcity of radio spectrum causes significant challenges for MNOs to address growing user demand for high data rates and capacity. In this regard, spectrum access models have an enormous role in how efficiently the limited amount of spectrum can be utilized. In general, using the static access model [31], the licensed spectrum is allocated in large chunks to MNOs of a country for a long time by the government agencies. However, a major bottleneck of the static access model is that, due to the exclusive right to use the allocated spectrum, a great portion of the licensed spectrum could be left unused in time, frequency, and space, while the other MNO may starve to avail the sufficient amount of the spectrum, resulting in an inefficient spectrum utilization countrywide resulting in poor spectrum utilization.

To address this spectrum under-utilization issue, in recent times, CR has appeared as an enabling technology. In CR, spectrum access is a major function, which prevents collisions between PUs and SUs to allow sharing of the licensed spectrum of one MNO with another to increase its effective spectrum bandwidth to serve high data rates and capacity. Depending on how the collisions between PUs and SUs are prevented while accessing any spectrum, there are three major categories of spectrum access techniques in CR systems, including interweave, underlay, and overlay. In this paper, we limit our focus to studying interweave and underlay spectrum access techniques.

In interweave access, SUs can opportunistically access only the spectrum not used by PUs. The fundamental idea behind the interweave model is to exploit the available under-utilized spectrum to reuse it in an opportunistic manner [32]-[33] without paying any cost [31]. More specifically, in the interweave model, the unused spectrum in time, frequency, and geographic location of licensed PUs can be shared opportunistically by SUs in a dynamic shared-use basis without interfering with PUs, for example, when PUs are inactive [31]. The standardization bodies have preferred the interweave cognitive radio model because of its applicability to addressing the under-utilization of the spectrum, as well as its ability to provide sufficient reliability and reasonably guaranteed Quality-Of-Service (QoS) [34]. However, even though interweave access needs additional spectrum sensing by SUs to find an idle spectrum of PUs, SUs are allowed to transmit at the maximum power.

In [10], the Interweave Strategy Based Shared-Use (ISSU) model for the dynamic spectrum access of licensed 28 GHz mmWave spectrum of one MNO to another under an in-building small cell scenario in a country has been proposed and stated as follows: "The licensed mmWave spectrum of one MNO, i.e., Primary-MNO (p-MNO) can be allowed to share with small cells in a building of another MNO, i.e., Secondary-MNO (s-MNO) only if no UE of p-MNO is present inside the corresponding building of small cells of s-MNO to avoid co-channel interference between UEs of p-MNO and s-MNO. If otherwise, no spectrum of p-MNO can be shared with in-building small cells of s-MNO."

Hence, using the interweave strategy, an s-MNO can access opportunistically the whole licensed spectrum of every single p-MNO in a country in time, frequency, and space so long as no UE of the respective p-MNO is present at the same time within the same building of small cells of s-MNO. In doing so, an s-MNO keeps sensing to detect the absence of the shared spectrum usage for each p-MNO within the building and camps on the shared spectrum of a p-MNO immediately at the absence of a UE of the corresponding p-MNO to operate s-MNO's small cells within the building.

However, in the underlay spectrum access, SUs can simultaneously access the spectrum of PUs at a reduced transmission power to serve its users subject to satisfying the interference threshold set by PUs. The underlay spectrum access technique takes advantage of several aspects. For example, the complex spectrum sensing mechanism in CR systems is not needed [35] since an SU can operate simultaneously with a PU at its spectrum. Hence, no further switching to detect an idle spectrum of PUs is needed. Additionally, this helps result in the possibility of interruption-less transmissions. Besides, due to limiting the transmission power of an SU to the interference threshold set by a PU, the underlay access is suitable for short-range communications. However, the underlay access suffers from the reduced transmission power of SUs to limit CCI to PUs.

In [11], the Underlay Cognitive Radio Spectrum Access (UCRSA) technique for the dynamic spectrum access of licensed 28 GHz mmWave spectrum of one MNO to another under an in-building small cell scenario in a country has been proposed and stated as follows: "The licensed 28 GHz mmWave spectrum of one MNO (i.e., p-MNO) can be allowed to share with small cells in a building of another MNO (i.e., s-MNO) subject to operating each small cell of the s-MNO at a reduced transmission power at any time irrespective of the existence of a UE of the p-MNO within the coverage of the corresponding small cell. The reduced transmission power is varied in accordance with the predefined interference threshold set by the p-MNO."

Hence, using the proposed technique, a small cell of an s-MNO can operate at its licensed 28 GHz mmWave spectrum at the maximum transmission power, whereas at a shared 28 GHz mmWave spectrum of any p-MNO at a reduced transmission power at any time corresponding to the predefined interference threshold set by the p-MNO to limit CCI to any UE of the p-MNO. Like, the conventional underlay spectrum access, the proposed technique does not require small cells of an s-MNO to keep sensing to detect the presence of UEs of any p-MNO to share with the spectrum of the p-MNO at any time.

Though both interweave and underlay have pros and cons as aforementioned, the combination of these two spectrum accesses can maximize the SE and EE. More specifically, SUs can explore interweave access when the spectrum of PUs is idle and underlay access when the spectrum of PUs is busy. This allows SUs to operate at the maximum power during an idle period in contrast to operating at reduced power when employing only the underlay access all the time.

In [14], a hybrid interweave-underlay spectrum access technique for the dynamic spectrum access of the licensed 28 GHz mmWave spectrum of one MNO to another under an in-building small cell scenario in a country has been proposed and stated as follows: "The licensed 28 GHz mmWave spectrum of one MNO (i.e., p-MNO) can be allowed to share with small cells in a building of another MNO (i.e., s-MNO) subject to operating each small cell of the s-MNO at the maximum transmission power if no UE of the p-MNO is present, but at a reduced transmission power if a UE of the p-MNO is present. The reduced transmission power is varied in accordance with the predefined interference threshold set by the p-MNO."

Hence, the proposed technique takes advantage of both the interweave as well as underlay access techniques. More specifically, using the interweave access, small cells of an s-MNO in a building can access opportunistically the whole licensed 28 GHz spectrum of every single p-MNO in a country in time, frequency, and space by operating them at the maximum transmission power as long as no UE of the respective p-MNO is present at the same time. But, if a UE of any p-MNO is present, following the underlay access, each small cell of the s-MNO immediately reduces its transmission power corresponding to the predefined interference threshold set by the p-MNO to limit CCI to the UE of the p-MNO. In this regard, the small cells of the s-MNO keep sensing to detect the presence of UEs for each p-MNO to update the corresponding spectrum access mode of operation to either the interweave access or the underlay access such that the CCI constraint to UEs of the respective p-MNO can be guaranteed.

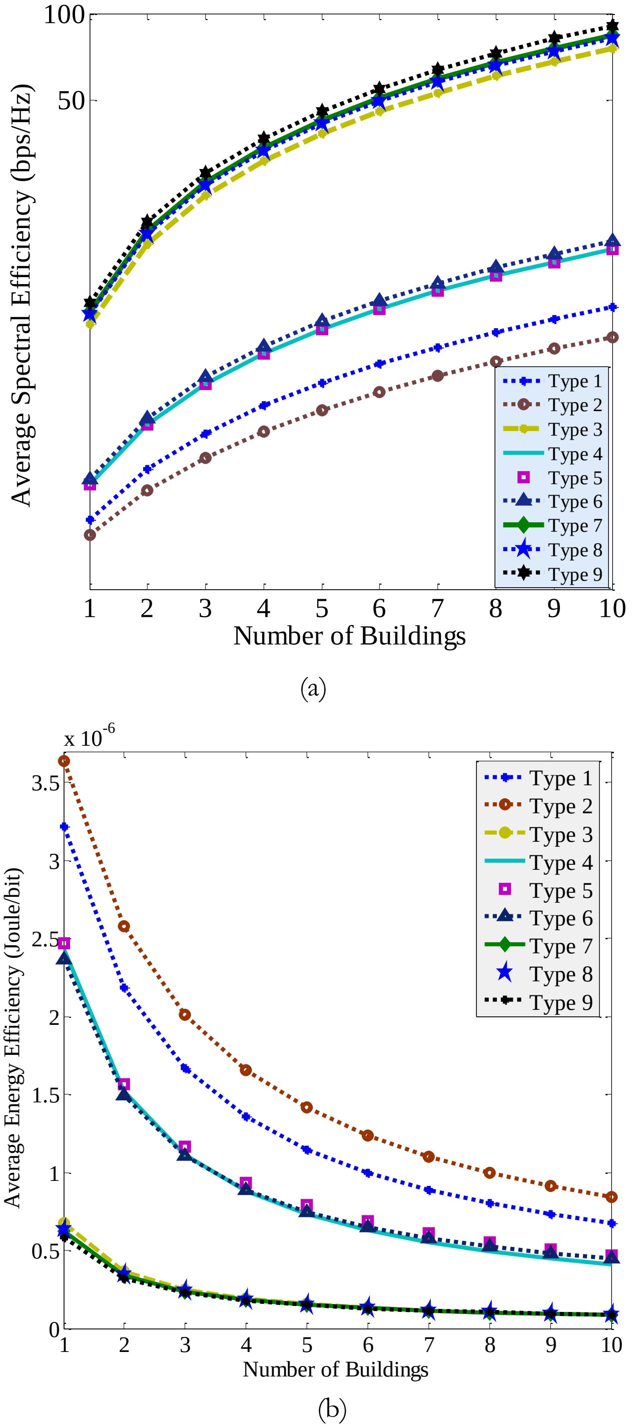
7. Performance Results

The following system architectures are considered to evaluate the enabling technologies for improving the network capacity indoors using small cells deployed in a building along each direction of the network capacity improvement triangle shown in Fig. 4. For the spectrum accessibility, numerous types of SBS architectures of an MNO are evaluated that share the spectrum of other systems, including another terrestrial MNO, a satellite system, and the 60 GHz unlicensed band [7]. For the SE improvement, cognitive radio techniques [10]-[11], [14] are evaluated for the DSS with a system architecture consisting of four MNOs in a country considered. Each MNO is allocated an equal amount of 28 GHz licensed spectrum that shares with the in-building small cells of other MNOs. For the network densification, each in-building SBS of an MNO is considered dual-band enabled, operating at the 28 GHz and 60 GHz mmWave spectrum [5]. For a given CCI constraint, the spectrum reuse is evaluated at both intra-and inter-building levels. Detailed parameters and assumptions can be found in the respective references cited (i.e., [5], [7], [10]-[11], [14]).

Hence, regarding spectrum accessibility, with extensive simulation and numerical results and analyses, it is shown in [7] that the network capacity and SE (Fig. 20(a)) can be improved by exploiting an SBS architecture to allow more spectrum to be available using the DSS techniques. The group of SBS architectures, including Types 9, 8, 7, and 3, gives significantly better SE responses than others due to better channel response of 60 GHz unlicensed spectrum than that of other licensed spectrums. Type 9 SBS architecture gives the best SE responses of all since an increase in the number of operating bands for an SBS increases the SE linearly.

Capacity and hence SE response of an in-building SBS depends on its architecture, which is directly affected by the channel characteristics as well as the number and amount of operating spectrum bands, the applied co-channel interference management strategy, and the rate of the traffic of the shared spectrum. Theoretically, the number of transceivers per SBS has no impact so long as there is no self-interference between transceivers and the characteristics as well as the number and amount of operating spectrum bands are kept unchanged.

Like SE, similar responses can be observed for EE (Fig. 20(b)), i.e. SBS architectures of Types 9, 8, 7, and 3 require the least energy per bit transmission, followed by Types 6, 5, and 4. It is to be noted that, unlike SE, the deviation in EE responses either among Types 9, 8, 7, and 3 or among Types 6, 5, and 4 are not significant. This is because, unlike SE, in addition to the density of SBSs, EE is the function of the number of transceivers, i.e. the aggregate transmission power of each SBS. For further information, please refer to [7].



(a)

(b)

Fig. 20. SE and EE responses of numerous SBS architectures.

Regarding SE improvement, by applying the ISSU model in [10], it is shown that, due to applying ISSU, the average capacity, as well as the SE, performances of an MNO (i.e., a serving MNO (s-MNO)) are improved by about 150%, whereas the EE performance is improved by about 60% (Fig. 21). Using Table 3 of [10], this is because the maximum amount of shared spectrum that can be obtained by employing ISSU to small cells in a building of an s-MNO is 1.5 times its licensed spectrum.

Since the average capacity and SE of an s-MNO are directly proportional, whereas the EE is inversely related, to its available spectrum, both the average capacity and SE performances are improved by 150%, whereas the EE, i.e. the energy required per bit transmission is reduced by 60% as shown in Fig. 21.

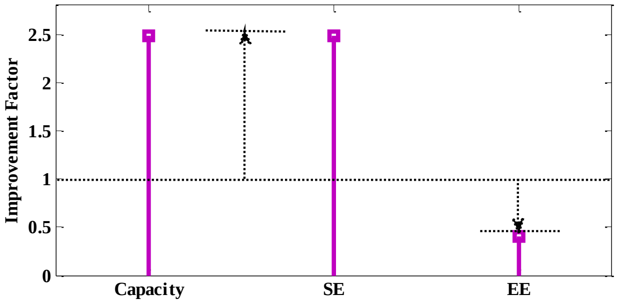


Fig. 21. Average capacity, SE, and EE performance improvement factors for an s-MNO with applying ISSU for a single building of small cells [10].

Further, by limiting the transmission power of an SBS to 20% of its maximum power, it is shown in [11] that the proposed underlay technique (i.e., UCRSA) can improve the average capacity and SE of an MNO by about 2.67 times, whereas EE by about 72.74% of, what can be obtained by the traditional Static Licensed Shared Access (SLSA) where each MNO is allocated exclusively to an equal amount of the licensed spectrum as shown in Fig. 22 [11].

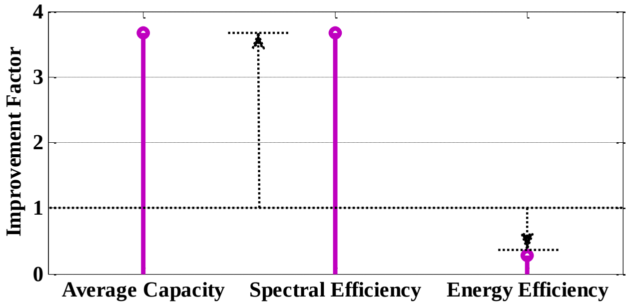


Fig. 22. Average capacity, SE, and EE improvement for MNO 1 of the proposed UCRSA technique over the traditional SLSA technique for a single building of small cells [11].

Furthermore, as shown in Fig. 23, by limiting the transmission power of an SBS to 20% of its maximum power, it is shown in [14] that the hybrid technique outperforms both the interweave and underlay techniques when each operating individually in terms of SE of an MNO. More specifically, the hybrid technique improves SE by about 2.82 times, whereas EE by about 73%, of MNO 1.

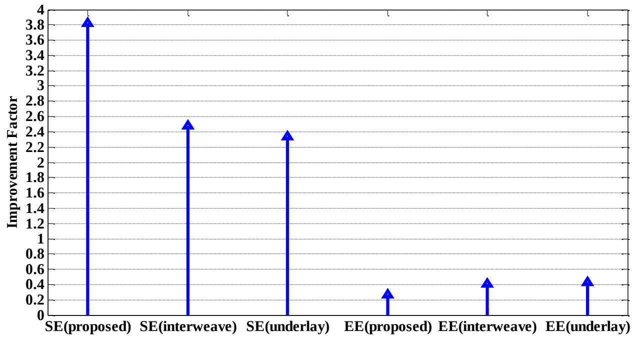
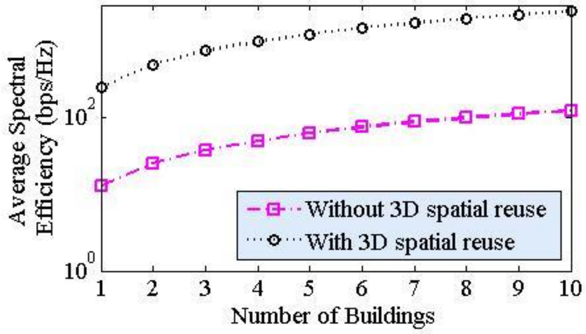


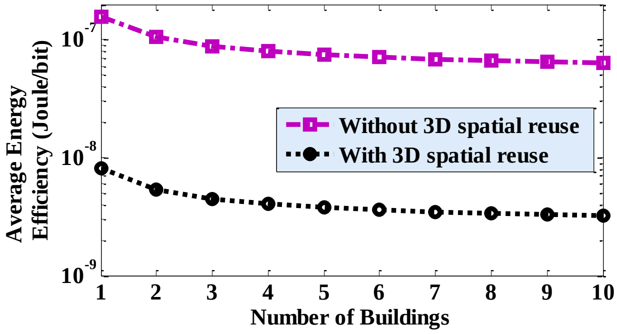
Fig. 23. SE and EE improvement factors for an s-MNO (i.e., MNO 1) due to applying different techniques for a single building of SBSs.

Finally, regarding the network densification, let $\alpha_f(d_{ter}) = 55\text{dB}$, $y_{\max,ter} = 2$, and $y_{\max,tra} = 8$ for the worst-case scenario. Let $\alpha_{thr,tra} = 0.25$. Assume that each SBS is dual-band enabled, operating at the 28 GHz and 60 GHz mmWave spectrum, respectively. Since the mmWave spectrum can be reused on each floor, we can then find the size of a 3D cluster for the 28 GHz (as well as 60 GHz) carrier spectrum $S_{3D} = S_{tra} \times S_{ter} = 1\times 9 = 9$. Now, consider that each multistory building consists of 10 floors each having 18 apartments such that the total number of apartments per building is 180. The total number of times the same mmWave spectrum can be reused to small cells per building is given by, $180/9 = 20$. Since the mmWave path loss indoors is frequency-dependent, which increases typically with an increase in frequency, we consider the lower 28 GHz mmWave path loss model to estimate an optimal 3D cluster size of small cells within a multistory building, which can apply to both 28 GHz, as well as 60 GHz spectrum bands [5].

Figure 24 shows SE and EE responses when applying 3D spatial reuse of mmWave spectrums to in-building small cells. From Fig. 24(a), it can be found that SE increases significantly when employing 3D spatial reuse of spectrums (i.e., Vertical Reuse Factor (vRF)) to small cells within each building as compared to when no reuse is considered. From Fig. 24(b), it can be found that EE improves exponentially with an increase in the number of buildings (i.e., Horizontal Reuse Factor (hRF)) and by a decent margin of about 20 times in the steady-state as

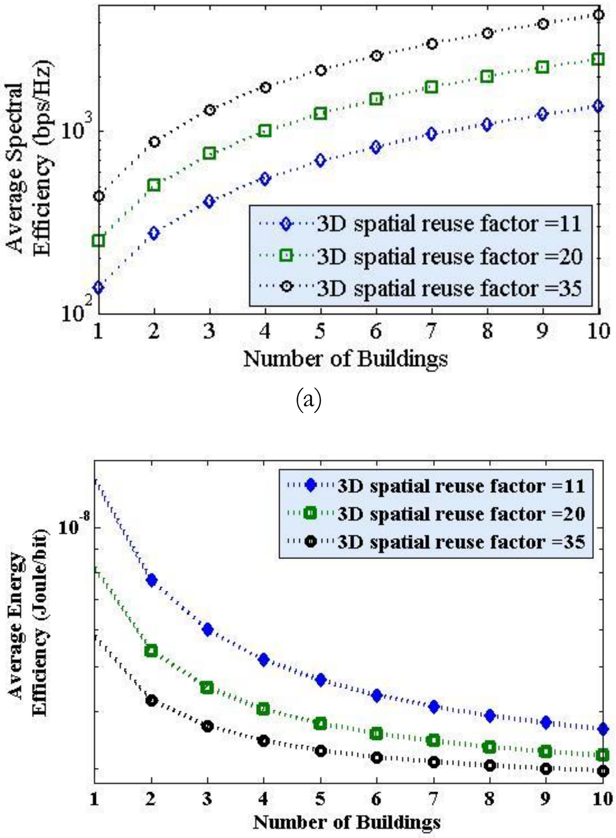


(a)



(b)

Fig. 24. Impact of applying 3D spatial reuse of mmWave spectra to in-building small cells: (a) system-level average SE; (b) system-level average EE [5].



(a)

(b)

Fig. 25. (a) Average SE and (b) Average EE responses for numerous 3D spatial reuse factors per building with variation in hRF, i.e. L [5].

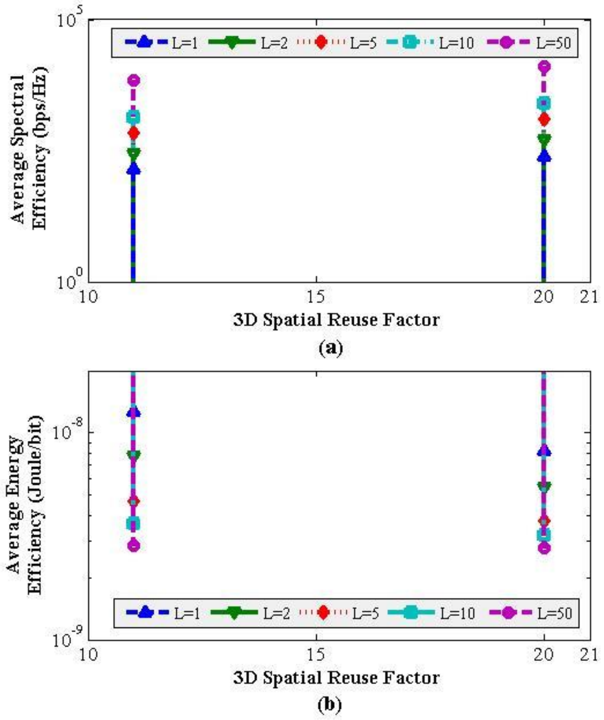


Fig. 26. (a) Average SE and (b) Average EE responses for different values of hRF (*L*) with the variation in 3D spatial reuse factor per building [5].

compared to when no 3D spatial reuse of spectra is exploited. Hence, exploiting 3D spatial reuse of mmWave spectra within multistorey buildings of small cells is a very effective technique to address the expected SE and EE requirements of beyond 5G mobile networks.

From Fig. 25(a), it can be found that SE improves linearly with an increase in hRF for any value of vRF. Similarly, from Fig. 26(a), SE improves linearly with an increase in vRF for any value of hRF. This implies that SE improves by a factor defined as the product of vRF and hRF, i.e. (vRF×hRF). However, from Fig. 25(b) and Fig. 26(b), it can be found that EE improves noticeably with an increase hRF for low values of vRF, i.e., 1≤hRF≤5, and no significant improvement in EE has been achieved even though vRF increases when hRF gets large enough (e.g., vRF=50). vRF mainly impacts SE enhancement irrespective of the values of hRF. Whereas vRF contributes to enhancing EE for low values of hRF. For more information, please refer to [5].

8. Conclusion

In this paper, we have provided a review on how to explore small cells to address the ever-growing high capacity demands of indoor users, particularly, in dense urban in-building scenarios. In this regard, we have considered exploring major three directions toward achieving high network capacity, including spectrum accessibility, spectral efficiency improvement, and network densification. A set of existing papers [5]-[7], [10]-[11], [14], highly relevant to the enabling technologies in each direction, have been reviewed under an in-building scenario to present the potentiality of small cells in achieving high capacity indoors. Relevant theoretical background in the context of in-building small cells has been discussed followed by the performance evaluation of major enabling technologies in each direction.

It has been shown that the following approaches in three directions can help achieve an enormous amount of in-building capacity, required by the existing, as well as future mobile networks.

- Multi-band multi-transceiver enabled small cells operating in the high-frequency millimeter-wave licensed or unlicensed spectrum to realize dynamic spectrum sharing techniques by exploiting small cell base station architectures subject to satisfying co-channel interference threshold for the spectrum accessibility,
- A hybrid spectrum access model (i.e., interweave-underlay spectrum access) in CR networks for the spectral efficiency improvement, and
- Exploiting both the vertical and horizontal spectrum reuse in small cells deployed densely within buildings for the network densification.

Acknowledgment

This paper is an extended version of a conference paper selected as one of the “Best Papers” at the Seventeenth International Conference on Wireless and Mobile Communications (ICWMC 2021), 18-22 July 2021 Nice, France [36]. This is a review paper, which is mainly based on the existing research works [5]-[7], [10]-[11], [14] mentioned in the reference section below. Consequently, in addition to [36], contents in this paper can be found merged with that in [5]-[7], [10]-[11], [14]. For interested readers, please refer to the relevant works for any sort of further information. References other than these are cited in the paper in the appropriate places, wherever used.

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Rony Kumer Saha received the Ph.D. degree in Electrical Engineering from Chulalongkorn University, Thailand, in 2017, the M.Eng. degree in Information and Communications Technologies from the Asian Institute of Technology, Thailand, in 2011, and the B.Sc. degree in Electrical and Electronic Engineering (securing second place in the batch) from Khulna University of Engineering and Technology, Bangladesh, in 2004.

He worked as a Postdoctoral Researcher with numerous laboratories, including Optical Access Network Laboratory, Wireless Platform Laboratory, and Radio and Spectrum Laboratory, of KDDI Research, Inc., Japan from June 2017 to January 2022. From September 2013 to July 2014, he was with East West University, Bangladesh. Before that, he worked as a Lecturer and was later promoted to Assistant Professor with American International University-Bangladesh (AIUB), Bangladesh, from January 2005 to August 2013. Currently, he is working as an Associate Professor with the Department of Electrical and Electronic Engineering, BRAC University, Dhaka, Bangladesh.

He has research experience on mobile wireless communications in universities and industries for *about 11 years*. He has authored *about 70 peer-reviewed*, reputed, and recognized international journal and conference papers. He also filed an international patent. He received the *Highest Evaluation* Score (Postdoctoral Fellow) for four consecutive fiscal-half years (2019-2020) at KDDI Research, Inc., Japan. His current research interests include 5G and beyond ultra-dense HetNets, licensed and unlicensed spectrum sharing, policy, and management in multiple communication systems, and millimeter-wave communications.

Previously, he served as a *member* of the Fronthaul Working Group, xRAN Forum, USA, and a *TPC Member* of the 2018 IEEE Global Communications Conference Workshops. He also served as the *Session Chair* for two sessions, namely, Radio Resource Management and Aerial Networks at the 2019 IEEE VTC-Fall, Honolulu, HI, USA, and the 2019 IEEE International Symposium on Dynamic Spectrum Access Networks Newark, Newark, NJ, USA, for the session Spectrum Sharing in 5G.

He also served as a Reviewer for several recognized journals, including IEEE Transactions on Wireless Communications, IEEE Transactions on Vehicular Technology, IEEE Wireless Communications, IEEE Access, Physical Communication (Elsevier), International Journal of Communication Systems (Wiley), Sensors Journal (MDPI), Symmetry Journal (MDPI), Mobile Information Systems (Hindawi), and Sustainability Journal (MDPI). He also served as a Steering Committee Member of IARIA ICSNC 2021. He has been serving as an *Associate Editor* of the Engineering Journal, Thailand, since 2019.

Dr. Saha has been supporting several International Academy, Research, and Industry Association (IARIA) conferences either as a member of the technical program committee, a panelist, a steering committee member, or a tutorial speaker. Further, he has made several scientific contributions to the IARIA conferences and received several Best Paper Awards (including ICSNC 2020 in Portugal, ICWMC 2021 in France, ICN 2021 in Portugal, and ICSNC 2021 in Spain). In recognition of outstanding scientific research results endorsed by international peers, exceptional scientific contribution to the IARIA events, and continuous leadership roles in IARIA conferences, Dr. Saha was awarded IARIA Fellow in 2021 Fall / 2022 Winter (http://www.iaria.org/fellows.html**)**.