On Achieving High Capacity using Small Cells in Multistory Buildings: A Review

Rony Kumer Saha
Radio and Spectrum Laboratory
KDDI Research, Inc.
2-1-15 Ohara, Fujimino-shi, Saitama, Japan
Email: ro-saha@kddi-research.jp

***Abstract*—In this paper, we review 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 explore existing works in three major directions toward improving the network capacity, including spectrum accessibility, spectral efficiency improvement, and network densification. It is shown that the exploitation of the Cognitive Radio technology to improve spectrum utilization and the 3-Dimensional (3D) spatial reuse of millimeter-wave spectrum with in-building multiband-enabled ultra-dense small cells to avail additional spectrum using Dynamic Spectrum Sharing can address enormous capacity demand in indoor mobile networks.**

***Keywords*—3D; small cell; network capacity; in-building; millimeter-wave; review; mobile network.**

I. Introduction

A. 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 encompassing 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.

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 1 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 a number of 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. 1), assuming that the Signal-to-Interference-plus-Noise-Ratio (SINR) is the same for both the macrocell and small cells.

Note that a small cell is a cellular radio access node that provides small coverage (typically in the order of 10 meters) at

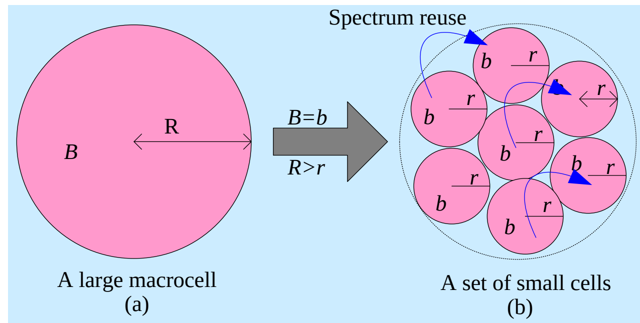

Figure 1. Formation of small cells from a large macrocell.

low power in both licensed and unlicensed spectrum bands to serve its users' mobile and Internet services. Small cells can be deployed by either 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. Femtocells are examples of small cells, and we use the terms “small cell” and “femtocell” interchangeably. Hence, because of a small coverage and a low transmission power, deploying Small Cell Base Stations (SBSs) within buildings as shown in Fig. 2 is considered an effective approach to serve such a large amount of indoor traffic at a high data rate.

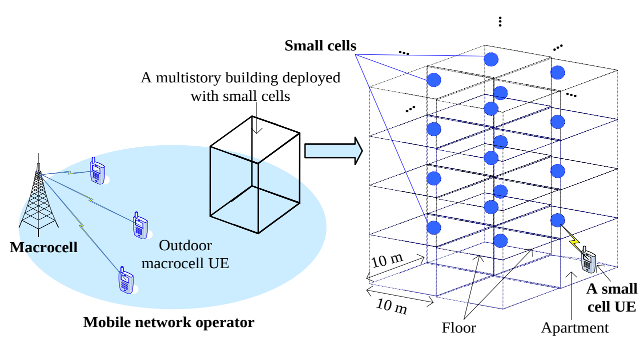

Figure 2. In-building small cell networks.

From Shannon’s capacity formula given in (1), it can be

$$C_L = \Phi \times B \operatorname{Log}_2\left(1+\left(\frac{P_r}{N+I_T}\right)\right) \quad (1)$$

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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.

observed that the network capacity can be improved mainly by addressing three directions, including spectrum accessibility, spectral efficiency improvement, and network densification. These are shown in a network capacity improvement triangle in Fig. 3 along with three directions. Corresponding enabling technologies to improve network capacity indoors using small cells deployed in a building are also shown along each direction.

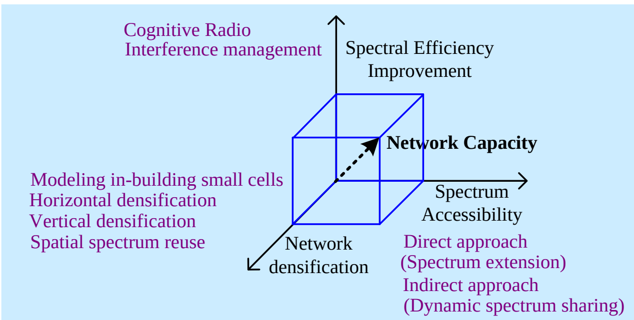

Figure 3. Network capacity improvement triangle.

B. *Related Work*

Numerous existing research studies have already addressed the enabling technologies along with the three directions [1]-[13]. For example, Saha [1] and Saha and Aswakul [2] have addressed the modeling of in-building small cells in the Millimeter-Wave (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 3-Dimensional (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 Spectral Efficiency (SE) indoors.

Further, Saha [3] 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. [4] 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. [5] have presented DSS with a view to improving their profit gain, as well as fairness.

Besides, the authors in [6]-[13] have addressed Cognitive Radio technology to address spectrum utilization. More specifically, Saha [6] has addressed an interweave spectrum access technique. Moreover, underlay spectrum access techniques by Saha [7], Khoshkholgh et al. [8], and Liang et al. [9], whereas hybrid interweave-underlay spectrum access techniques by Saha [10], Khan et al. [11], Zuo et al. [12], and Mehmeti et al. [13], have been addressed. It has been shown in [6]-[7], [10] 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 [10]. 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.

C. *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 [1]-[3], [6]-[7], [10]. 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.

D. *Organization*

The paper is organized as follows. In Section II, spectrum accessibility is discussed under both direct and indirect approaches. Section III covers spectral efficiency improvement techniques, particularly, interweave, underlay and hybrid, spectrum access approaches. In Section IV, in-building network densification and spectrum reuse strategies are presented. Performance results based on [1]-[3], [6]-[7], [10] along three directions toward achieving high in-building capacity are evaluated in Section V. We conclude the paper in Section VI. A list of abbreviations is given in Appendix I.

II. 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 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. Available spectrum for a Mobile Network Operator (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. 4), be it contiguous or noncontiguous. However, the traditional direct approaches to extend spectrum are no more effective due to the scarcity of radio spectrum availability, particularly below 3 GHz [14], as well as a 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

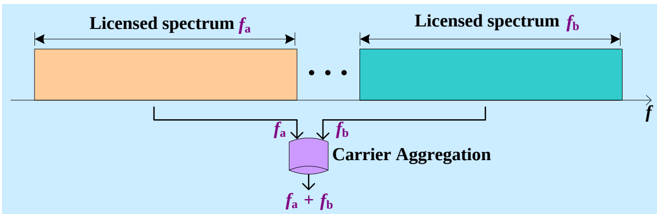

Figure 4. Spectrum access using the Carrier Aggregation approach.

satisfying the condition that the primary system is not affected due to sharing. Such an approach can be termed Dynamic Spectrum Sharing (DSS). Small cells indoors can play a crucial role in DSS.

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 [3]. More specifically, in [3], by enabling SBSs with a single-/multiple-transceiver and operating them at either a single or multiple licensed/unlicensed spectra of homogeneous/ heterogeneous systems, a total of nine 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).

For convenience, a multi-transceiver multiband enabled SBSs operating in the licensed and unlicensed spectrums is shown in Fig. 5. One of the transceivers of an SBS operates at

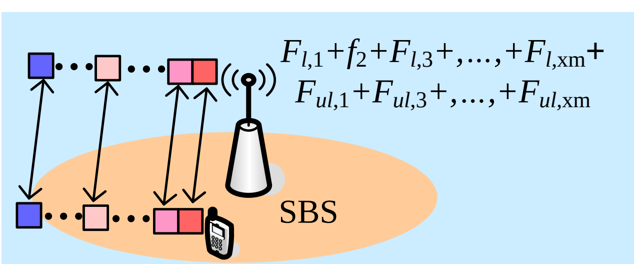

Figure 5. Type 9 SBS. $F_{l,x} \in \boldsymbol{F}_{l,x} = \{F_{l,1}, F_{l,2}, \ldots, F_{l,\text{xm}}\}$ and $F_{ul,x} \in \boldsymbol{F}_{ul,x} = \{F_{ul,1}, F_{ul,2}, \ldots, F_{ul,\text{xm}}\}$ denote, respectively, a set of licensed spectra of other systems than any mobile system (e.g., satellite systems) and a set of unlicensed spectra (e.g., 60-GHz, 5-GHz, and 2.4-GHz) [3].

the spectrum of its own MNO, 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. Hence, 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 [3].

To avoid Co-Channel Interference (CCI) when sharing the licensed spectrum of homogeneous/ heterogeneous system, Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) 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. 6 is applied to any transceiver of an SBS depending on its operating spectrum. An ABS is a Transmission Time Interval (TTI) during which no data signal is transmitted

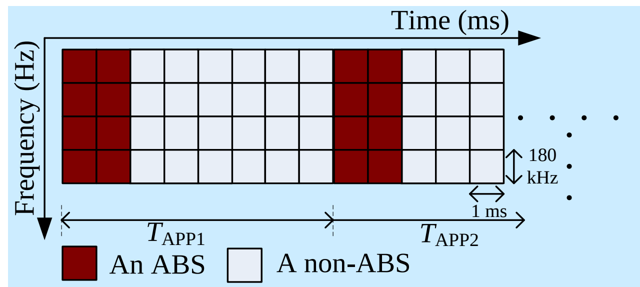

Figure 6. An illustration of the ABS-based eICIC technique [3]. T_{APP1} and T_{APP2} denote APP 1 and APP 2, respectively.

except for some control signals 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 [3]. Note that for an unlicensed band, no CCI is considered.

III. 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 primary User Equipments (UEs) and Secondary UEs (SUs) to allow sharing the licensed spectrum of one MNO with another to increase its effective spectrum bandwidth, resulting in improving its spectral efficiency to serve high capacity. Based on how the collisions between primary and secondary UEs 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 on studying interweave and underlay spectrum access techniques.

In the interweave model, the unused spectrum in time, frequency, and geographic location of licensed primary UEs

(PUs) can be shared opportunistically by SUs in a dynamic shared-use basis without interfering PUs, for example, when PUs are inactive [15]. To find an idle spectrum of PUs, SUs need to be able to sense the used spectrum of PUs. Once sensed idle, SUs can transmit at the maximum power. In [6], an 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* [6].

However, in underlay 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. Unlike the interweave access, the underlay access does not need any spectrum sensing. However, it suffers from the reduced transmission power of SUs to limit CCI to PUs. In [7], an Underlay Cognitive Radio Spectrum Access (UCRSA) technique for the dynamic spectrum access of licensed 28 GHz mmWave spectrum of one MNO to another under 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* [7].

Though both interweave and underlay have pros and cons as aforementioned, the combination of these two spectrum accesses can maximize the SE. More specifically, SUs can explore interweave access when the spectrum of PUs is idle and the underlay access when the spectrum of PUs is busy. In [10], 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 is 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 [10]. The reduced transmission power is varied in accordance with the predefined interference threshold set by the p-MNO.*

IV. Network Densification

SBSs can be deployed both in 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 the reuse of mmWave spectra in ultra-dense deployed small cells within the building.

In [1], a minimum separation distance for the intra-floor level and inter-floor-level are expressed numerically for the 28 GHz mmWave spectrum to define a set to SBSs (also called a cluster of SBSs) corresponding to the minimum distances both intra-floor and inter-floor levels subject to satisfying co-channel interference constraints in both levels. The size of a 3D cluster of SBSs is then defined such that the same spectrum bandwidth can be reused in each cluster of SBSs. Figure 7 shows an example minimum distance constraint-based 3D cluster of SBSs with respect to floor n+1. Region of Exclusions (RoEs) for both intra-and inter-floor levels are shown with red

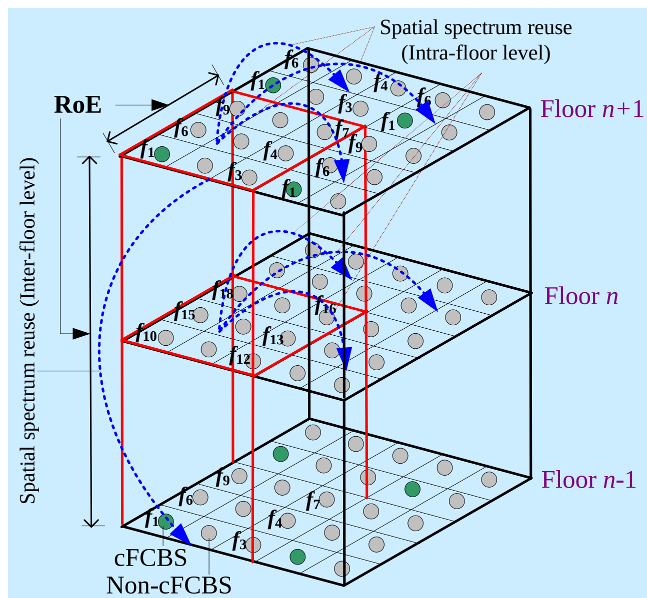

Figure 7. Formation of an in-building 3D cluster of SBSs subject to satisfying the minimum distance constraints in both intra-and inter-floor levels to reuse the same spectrum in a 3D in-building scenario [2].

color lines. Green color circles represent Co-channel SBSs (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 [2].

V. Performance Results

Default parameters and assumptions used for generating the following performance responses can be found in the respective references cited (i.e., [1]-[3], [6]-[7], [10]). Hence, regarding spectrum accessibility, with extensive simulation and numerical results and analyses, it is shown in [3] that the network capacity and SE (Fig. 8) can be improved by exploiting an SBS architecture to allow more spectrum to be available using the DSS technique. SBS architectures, including Types 9, 8, 7, and 3, give better SE responses than others due to operating in the 60-GHz unlicensed spectrum providing better channel responses than that of other licensed spectrums. For further information, please refer to [3].

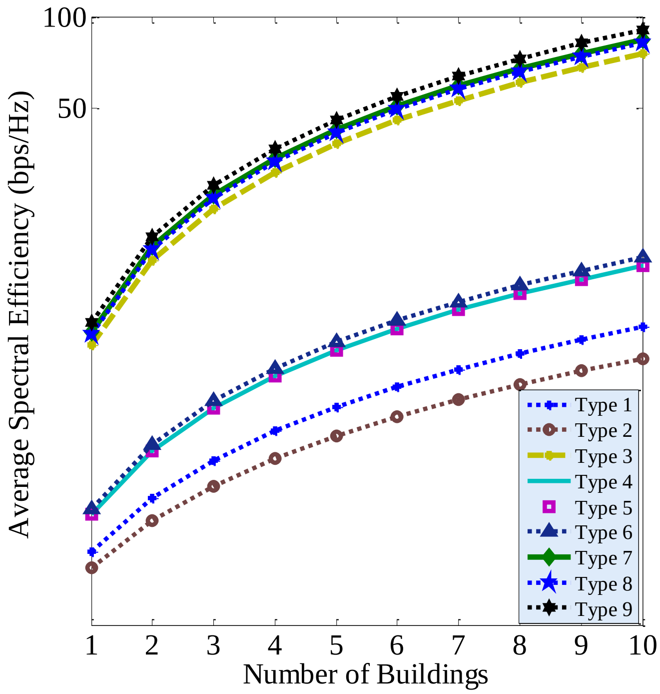

Figure 8. SE responses of numerous SBS architectures [3].

Regarding SE improvement, by applying the ISSU model in [6], it is shown that the average capacity, as well as the SE, performances of an MNO (i.e., an s-MNO) are improved by about 150% as shown in Fig. 9. Further, by limiting the transmission power of an SBS to 20% of its maximum power, it is shown in [7] that the proposed underlay technique (i.e., UCRSA) can improve the average capacity and SE of an MNO by about 2.67 times 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. 10 [7]. Furthermore, as shown in Fig. 11, by limiting the transmission power of an SBS to 20% of its maximum power, it is shown in [10] that the hybrid technique outperforms both the interweave and underlay techniques when each operating individually in terms of SE of an MNO.

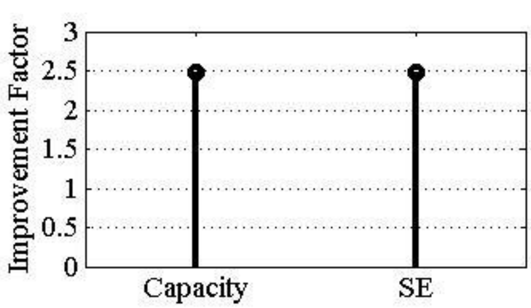

Figure 9. Average capacity and SE performance improvement factors for an s-MNO with applying ISSU for a single building of small cells [6].

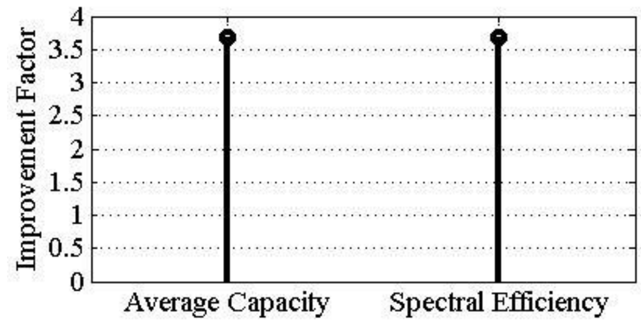

Figure 10. Average capacity and SE improvement for an MNO due to applying the UCRSA technique over that of the SLSA technique for a single building of small cells [7].

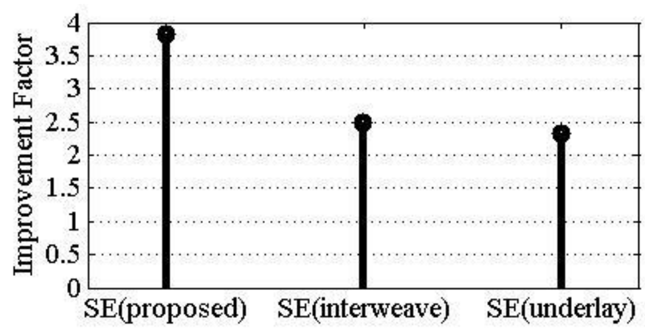

Figure 11. SE improvement factors for an s-MNO due to applying, interweave, underlay, and the proposed hybrid inter-weave-underlay techniques for a single building of SBSs [10].

Finally, regarding the network densification, with extensive simulation results in [2], it is shown in Fig.12 that the SE increases significantly when employing 3D spatial reuse of the

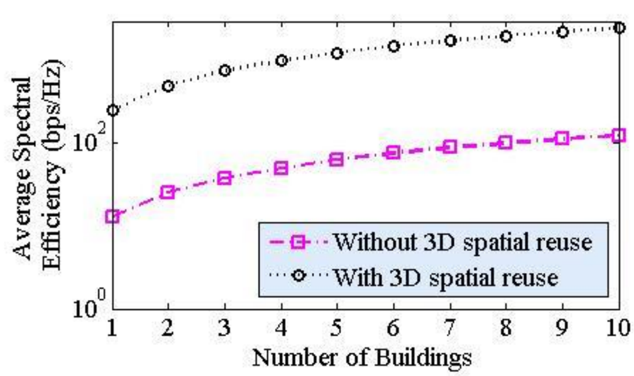

Figure 12. Impact of applying 3D spatial reuse of mmWave spectra to in-building small cells on the average SE [1].

same spectrum (i.e., Vertical Reuse Factor (vRF)) to small cells within each building as compared to when no reuse is considered. Also, in Fig.13, it is shown that the SE improves

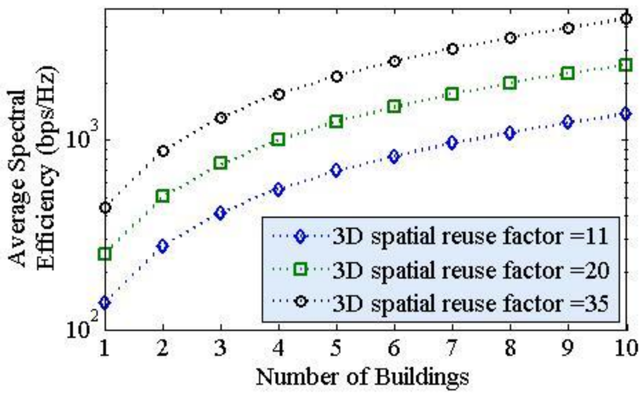

Figure 13. Average SE response for numerous 3D spatial reuse factors per building with a variation in the number of buildings of SBSs (i.e., hRF) [1].

linearly with an increase in Horizontal Reuse Factor (hRF) for any value of vRF such that the overall SE improves by a factor defined as the product of vRF and hRF, i.e., (vRF×hRF).

VI. 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 [1]-[3], [6]-[7], [10] highly relevant to the enabling technologies along 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 along each direction.

It has been shown that the following approaches along 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 Cognitive Radio 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.

APPENDIX I

A LIST OF ABBREVIATIONS

Abbreviation	Description
2D	2-Dimensional
3D	3-Dimensional
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
eICIC	Enhanced Intercell Interference Coordination
hRF	Horizontal Reuse Factor
LAA	Licensed Assisted Access
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

ACKNOWLEDGMENT

This is a review paper, which is mainly based on the author's existing research works [1-3], [6-7], [10] mentioned in the reference section below. Consequently, contents in this paper, in terms of texts, figures, equations, and other forms, can be found merged substantially with that in [1-3], [6-7], [10]. 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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