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

Author: Rony Kumer Saha

Presented by
Rony Kumer Saha, Ph.D.
Radio and Spectrum Laboratory
Future Network Infrastructure Division 2
ADVANCED TECHNOLOGY LABORATORY

KDDI Research, Inc. JAPAN
2-1-15 Ohara, Fujimino-shi, Saitama, 356-8502
email: ro-saha@kddi-research.jp

Resume of the Presenter

RONY KUMER SAHA received the B.Sc. degree in electrical and electronic engineering from the Khulna University of Engineering and Technology, KUET, in 2004, the M.Eng. degree in information and communications technologies from the Asian Institute of Technology (AIT), Thailand, in 2011, and the Ph.D. degree in electrical engineering from Chulalongkorn University, Thailand, in 2017. Since 2017, he has been working as a Postdoctoral Fellow/Research Engineer with the Radio and Spectrum Laboratory, KDDI Research, Inc., Japan.

He worked as a Lecturer and later promoted to an Assistant Professor with American International University-Bangladesh, Bangladesh, AIUB, from January 2005 to August 2013. From September 2013 to July 2014, he was with East West University, Bangladesh. His current research interests include 5G and beyond ultra-dense HetNets, spectrum sharing, policy, and management in multiple communication systems, and millimeter-wave communications. He has research experiences on mobile wireless communications in universities and industries for more than ten years. He has authored about 60 peer-reviewed, reputed, and highly recognized international journal and conference papers. He also filed an international patent.

Dr. Saha served as a member of the Fronthaul Working Group, xRAN Forum, USA. He also served as a TPC member of the 2020 ICSNC and 2018 IEEE Global Communications Conference Workshops. Furthermore, he also served as the Session Chair for two sessions, namely Radio Resource Management and Aerial Networks at 2019 IEEE VTC-Fall, Hawaii, USA, as well as the 2019 IEEE International Symposium on Dynamic Spectrum Access Networks Newark, NJ, USA, for the session Spectrum Sharing in 5G. Since early 2019, he has been serving as an Associate Editor of the Engineering Journal, Thailand. He served as a Reviewer of a number of recognized journals, including IEEE Transactions on Vehicular Technology, IEEE Access, Elsevier Physical Communication, Wiley International Journal of Communication Systems, MDPI Sensors Journal, MDPI Symmetry Journal, Hindawi Mobile Information Systems, and MDPI Sustainability Journal.

Topics of Research Interests

- Terahertz and millimeter wave communications
- 5G NR-U: 5G New Radio on Unlicensed Bands
- Dynamic spectrum sharing and policy for 5G and beyond mobile networks
- Cognitive radio networks and spectrum sensing techniques
- Co-channel interference analysis, mitigation, avoidance, and cancellation strategies
- In-building small cell network planning, design and deployment
- Planning, design and development of spectrum sharing algorithm for homogeneous (mobile networks) and heterogeneous networks (mobile networks and satellite networks)
- Radio resource allocation and scheduling policy and algorithm
- Mobile MAC layer and physical layer issues
- Proof-of-concept evaluation of virtualization and Slicing of 5G radio access network (RAN)
- Cloud RAN (CRAN) in 5G era
- Fronthaul design for CRAN

Presentation Outline

- Background and Problem Statement
- Spectrum Accessibility
  - Spectral Efficiency Improvement
  - Network Densification
    - Performance Results
    - Conclusion
      - References

Background and Problem Statement (1)

PROBLEM

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.

Serving this large amount of indoor data at a high rate with an outdoor Macrocell Base Station (MBS) is difficult 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.

OVERCOME

How to address indoor high data rates and enormous capacity demands?

Background and Problem Statement (2)

OVERCOME

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.**

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*.

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.

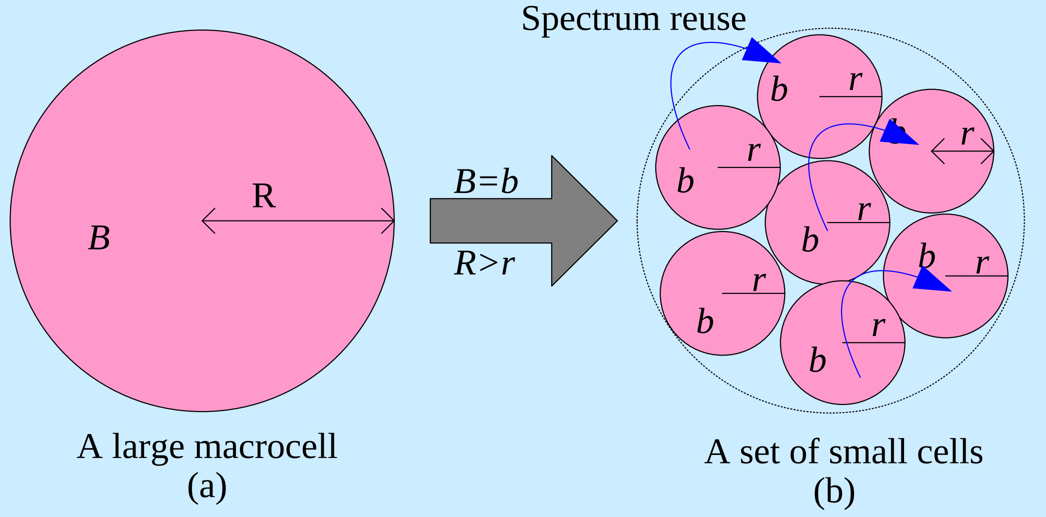

Figure 1. Formation of small cells from a large macrocell.

$$C_S = x \times C_M$$

where
C_M denotes the macrocell capacity
C_S denotes the total small cell capacity
x denotes spectrum reuse factor

Background and Problem Statement (3)

OVERCOME

A small cell is a cellular radio access node that provides small coverage (typically in the order of 10 meters) at low power in both licensed and unlicensed spectrum bands to serve its users' mobile and Internet services.

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.

Because of a **small coverage and a low transmission power**, deploying Small Cell Base Stations (SBSs) within buildings as shown in Figure 2 is considered an *effective approach to serve such a large amount of indoor traffic at a high data rate.*

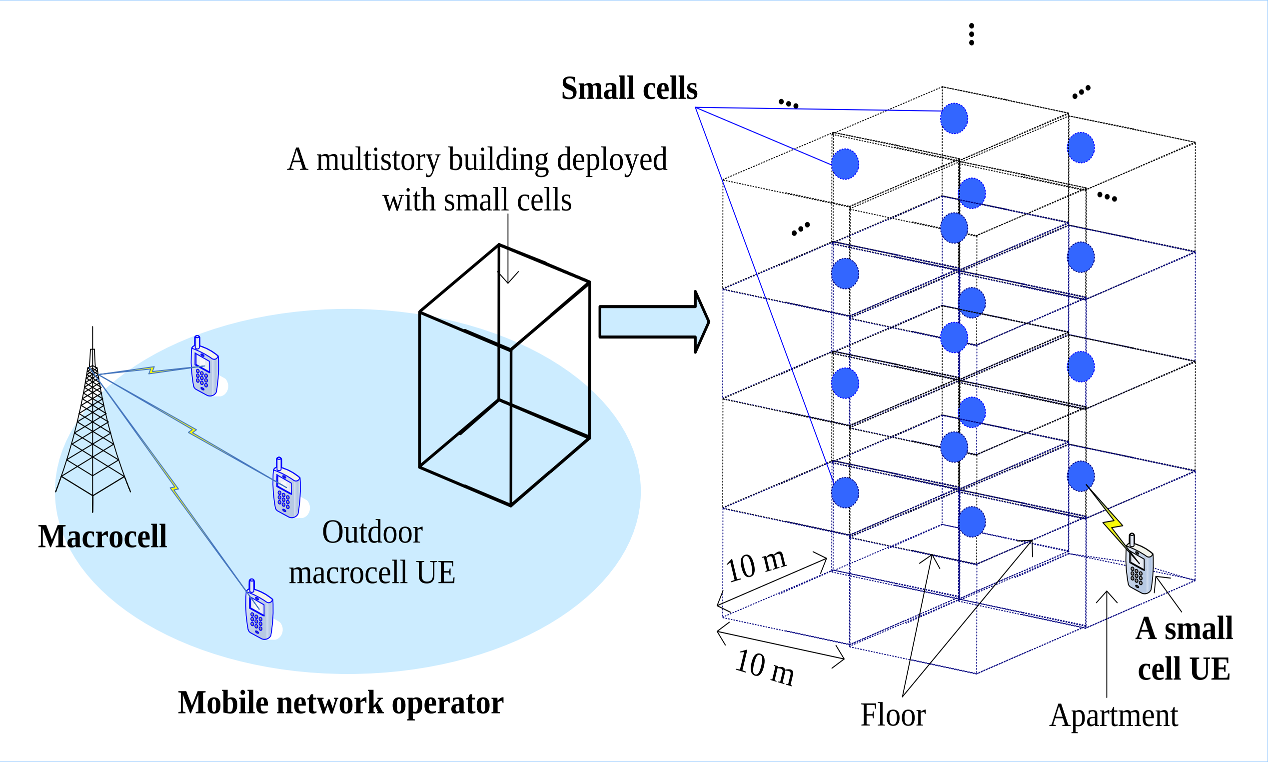

Figure 2. In-building small cell networks.

Background and Problem Statement (4)

OVERCOME

From Shannon's capacity formula given in (1), the **network capacity** can be *improved* mainly by addressing three directions:

1. spectrum accessibility,
2. spectral efficiency improvement, and
3. network densification.

These are shown in a *network capacity improvement triangle* in Figure 3 along with three directions.

Spectrum reuse factor — Received desired signal power

$$\text{Achievable Capacity } C_L = \Phi \times B \,\mathrm{Log}_2\left(1+\left(\frac{P_r}{N+I_T}\right)\right) \quad (1)$$

Available bandwidth — Noise — Received total interference signal power

Corresponding **enabling technologies** to improve network capacity indoors using small cells deployed in a building are also shown along each direction.

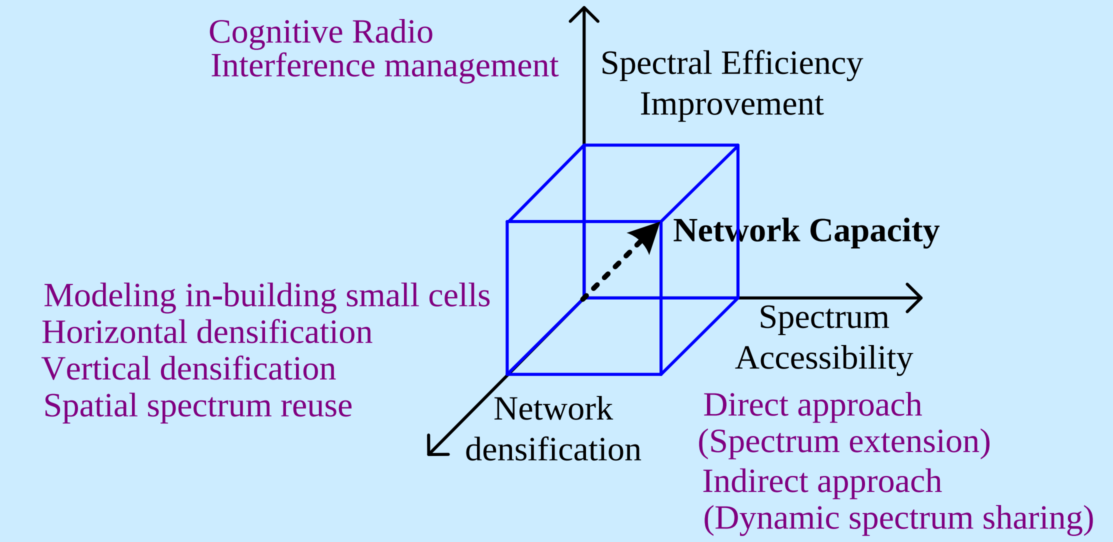

Figure 3. Network capacity improvement triangle.

Background and Problem Statement (5)

RELATED WORK

Numerous existing research studies have already addressed the *enabling technologies* along with the **three directions [1-13]**.

Saha [1] and Saha and Aswakul [2] have addressed

- *modeling of in-building small cells* in the Millimeter-Wave (mmWave) and microwave spectrum bands, respectively.
- defining a 3-Dimensional (3D) cluster of small cells to *reuse the same spectrum* in each 3D cluster of small cells within a building.
- Also, *showing both horizontal densification* of small cells on each floor, as well as *vertical densification of small cells* between floors within each building, can achieve high capacity and Spectral Efficiency (SE) indoors.

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.

Also the **authors in [4-6]** have addressed

- *Cognitive Radio technology* to improve the overall spectrum utilization.

Background and Problem Statement (5)

RELATED WORK

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.

Background and Problem Statement (6)

LIMITATION

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.

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].**

Spectrum Accessibility

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 millimetre-wave (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 (Figure 4), be it contiguous or noncontiguous.

Bottleneck: *no more effective* due to the scarcity of radio spectrum availability, particularly below 3 GHz [7], as well as a huge cost of licensing spectrum.

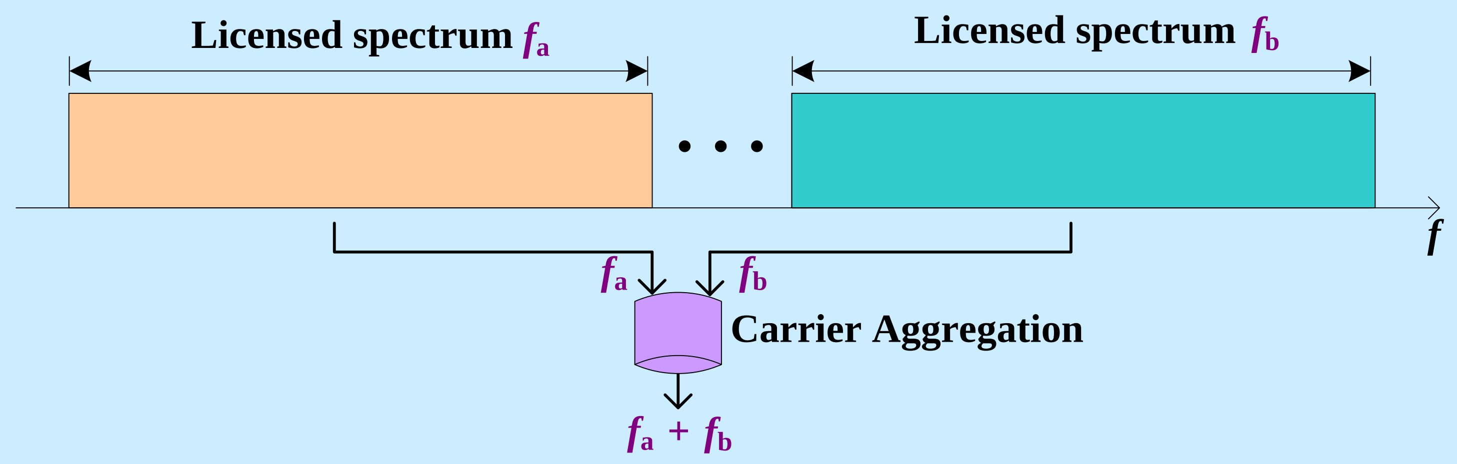

Figure 4. Spectrum access using Carrier Aggregation approach.

Spectrum Accessibility

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 **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).*

Spectrum Accessibility

A **multi-transceiver multiband enabled SBSs** operating in the licensed and unlicensed spectrums is shown in Figure 5.

- **One** of the transceivers of an SBS operates at the spectrum of its own MNO,
- the **second t**ransceiver 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].

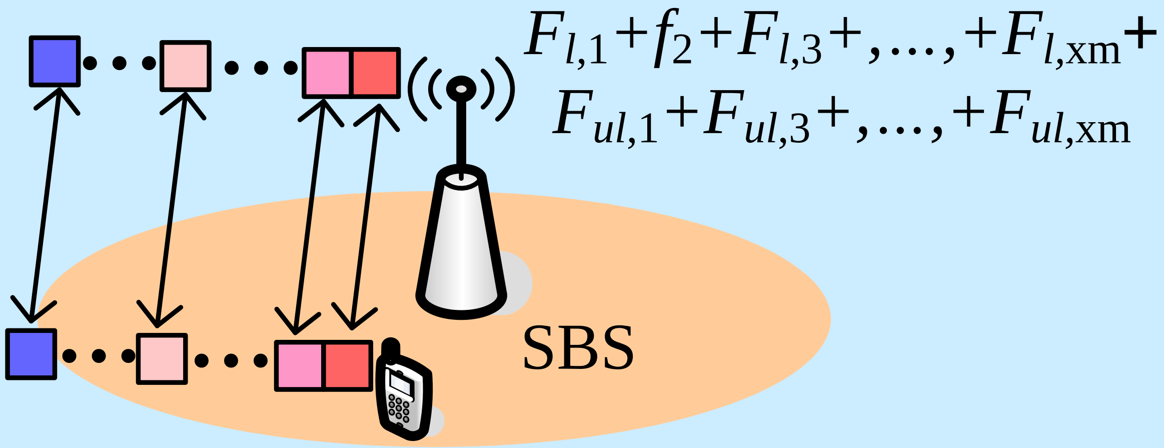

Figure 5. Type 9 SBS. $F_{l,x} \in \boldsymbol{F_{l,x}} = \{F_{l,1}, F_{l,2}, \dots, F_{l,\text{xm}}\}$ and $F_{ul,x} \in \boldsymbol{F_{ul,x}} = \{F_{ul,1}, F_{ul,2}, \dots, F_{ul,\text{xm}}\}$ denote, respectively, a set of licensed spectra of other systems than any mobile system (e.g., satellite systems)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

Interference Management

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 Figure 6 is *applied to any transceiver of an SBS* depending on its operating spectrum.

Note that for an *unlicensed band*, no CCI is considered.

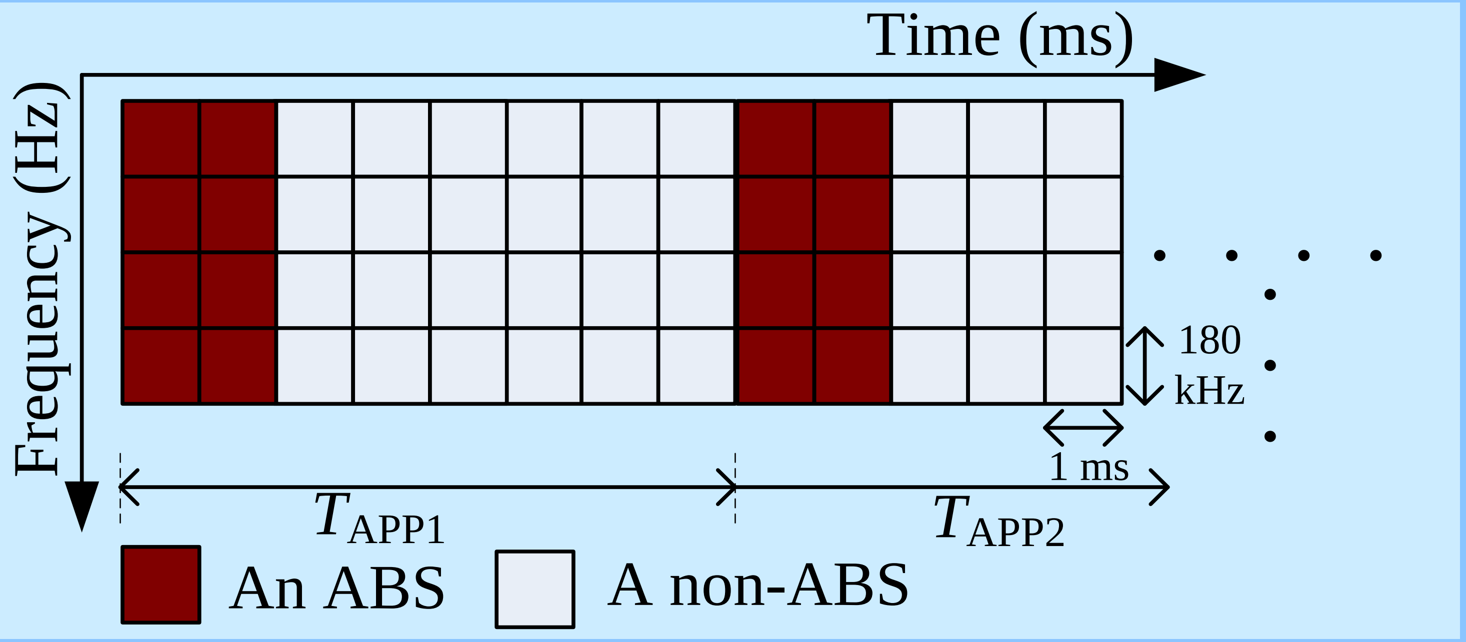

Figure 6. An illustration of the ABS-based eICIC technique [3]. T_{APP1} and T_{APP2} denote APP 1 and APP 2, respectively.

Spectral Efficiency Improvement

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, which prevents collisions between primary User Equipments (UEs) and Secondary UEs (SUs) to *allows 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.

Interweave Spectrum Access Model

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].

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 is **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].

Underlay Spectrum Access Model

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].

Hybrid Interweave-Underlay Spectrum Access Model

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.

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 [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.*

Network Densification

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 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].

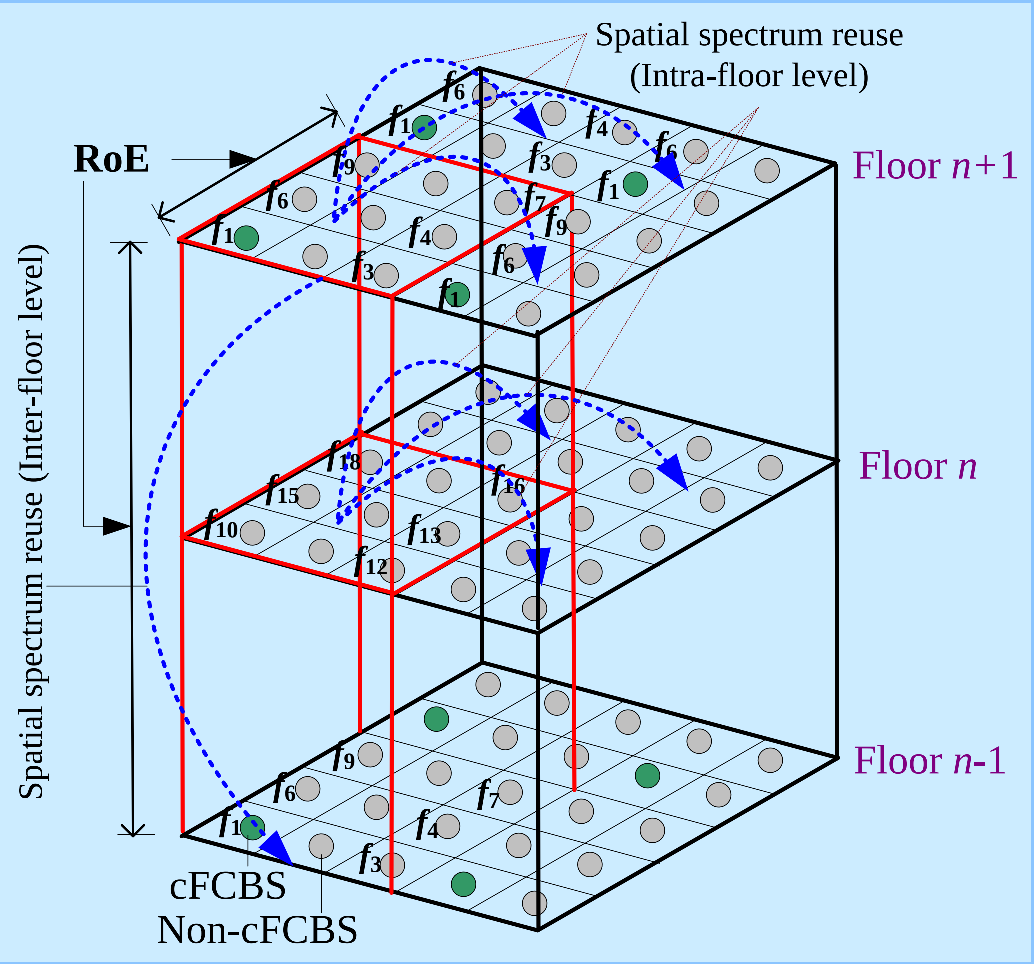

Figure 7. Formation of an in-building 3D cluster of SBSs subject to satisfying the minimum distance constraints in both intra-and inter-floor levels to reuse the same spectrum in a 3D in-building scenario [2].

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 (Figure 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.

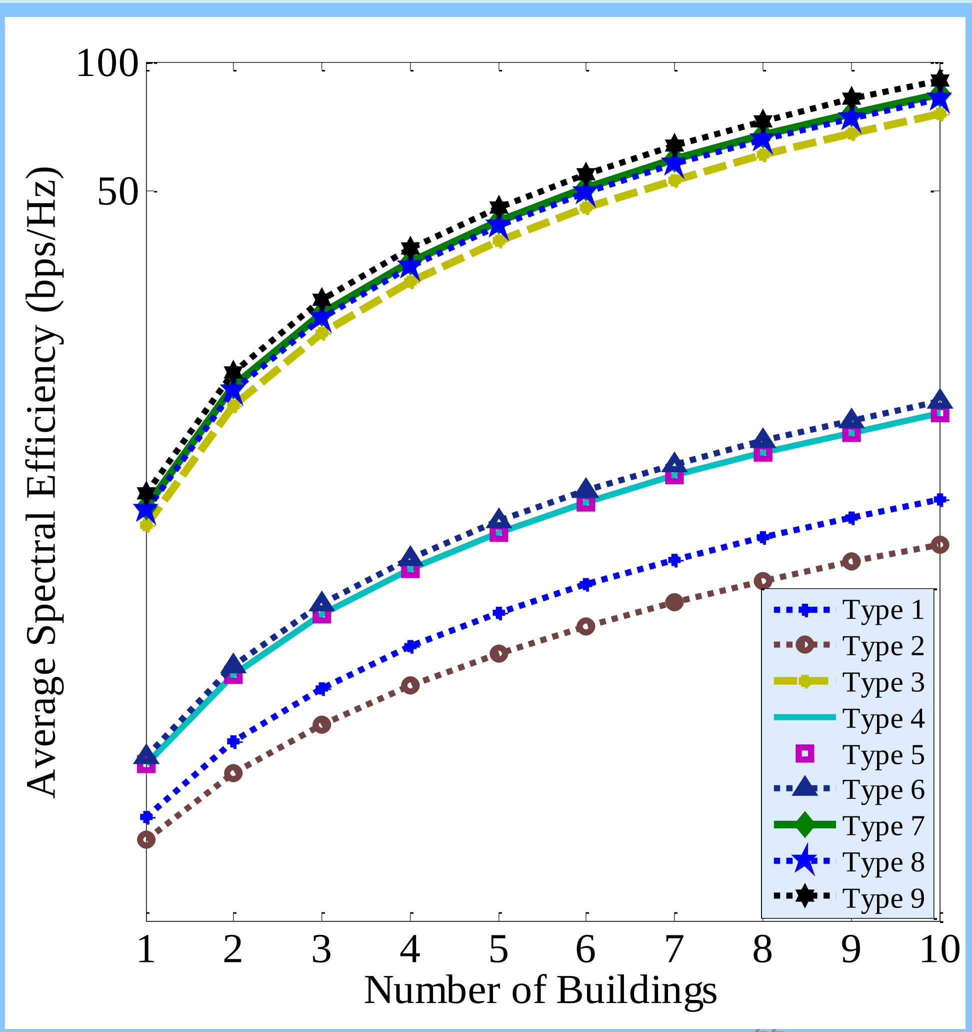

Figure 8. SE responses of numerous SBS architectures [3].

Spectrum Efficiency Improvement

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 Figure* 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 Figure 10 [7].

Furthermore, as shown in Figure 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.

Spectrum Efficiency Improvement

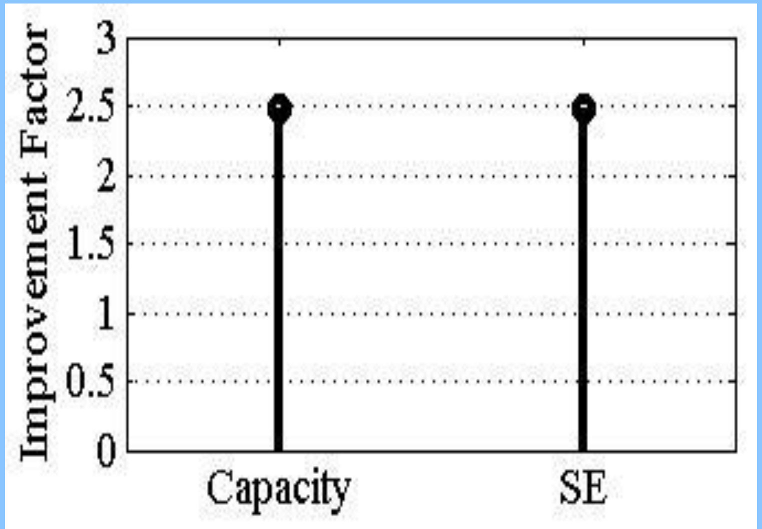

Figure 9. Average capacity and SE performance improvement factors for an s-MNO with applying ISSU for a single building of small cells [6].

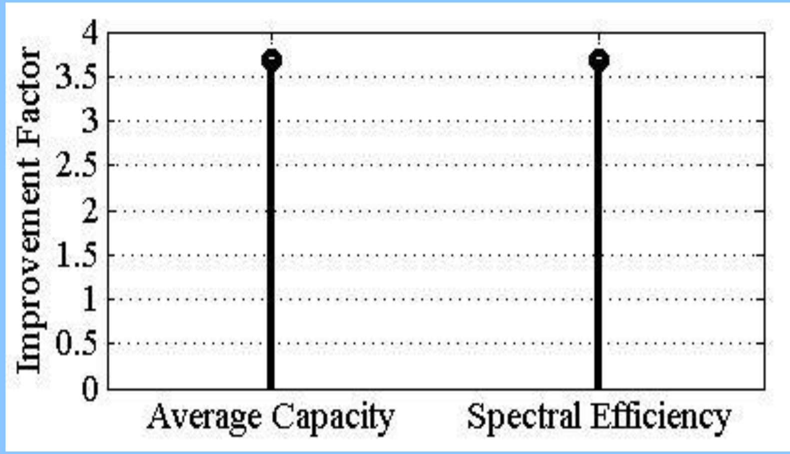

Figure 10. Average capacity and SE improvement for an MNO due to applying the UCRSA technique over that of the SLSA technique for a single building of small cells [7].

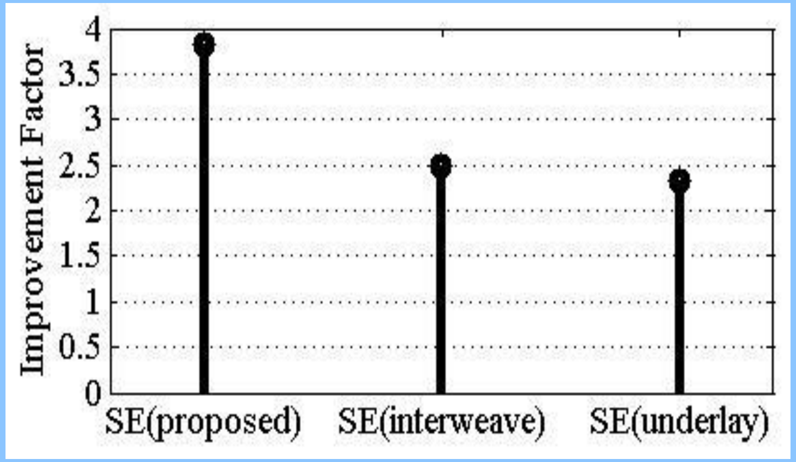

Figure 11. SE improvement factors for an s-MNO due to applying, interweave, underlay, and the proposed hybrid inter-weave-underlay techniques for a single building of SBSs [10].

Network Densification

Regarding **the network densificatio**n, with extensive simulation results in [2], it is shown in **Figure 12** that the SE increases significantly when employing 3D spatial reuse of the same spectrum (i.e., Vertical Reuse Factor (vRF)) to small cells within each building as compared to when no reuse is considered.

Also, in **Figure 13**, it is shown that the SE improves 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).

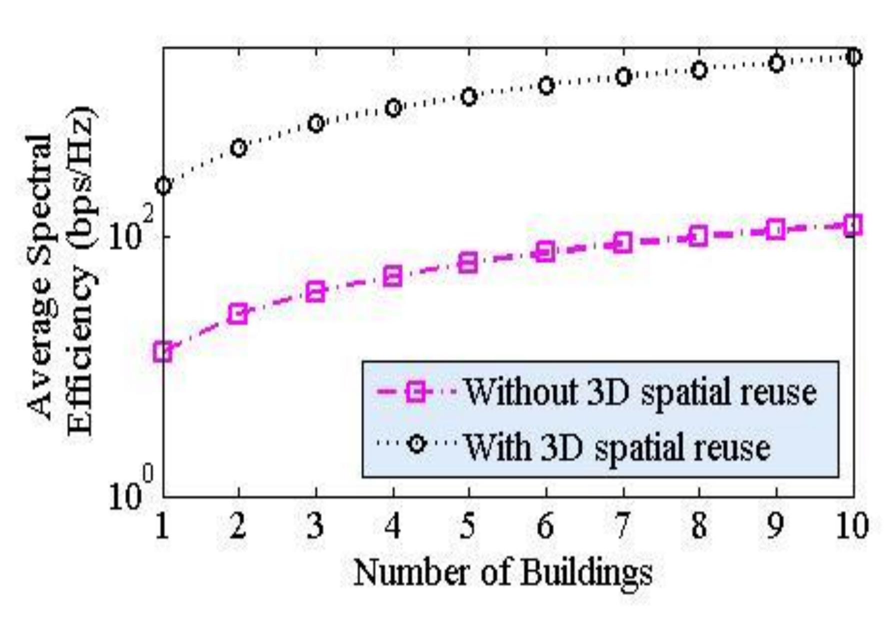

Figure 12. Impact of applying 3D spatial reuse of mmWave spectra to in-building small cells on the average SE [1].

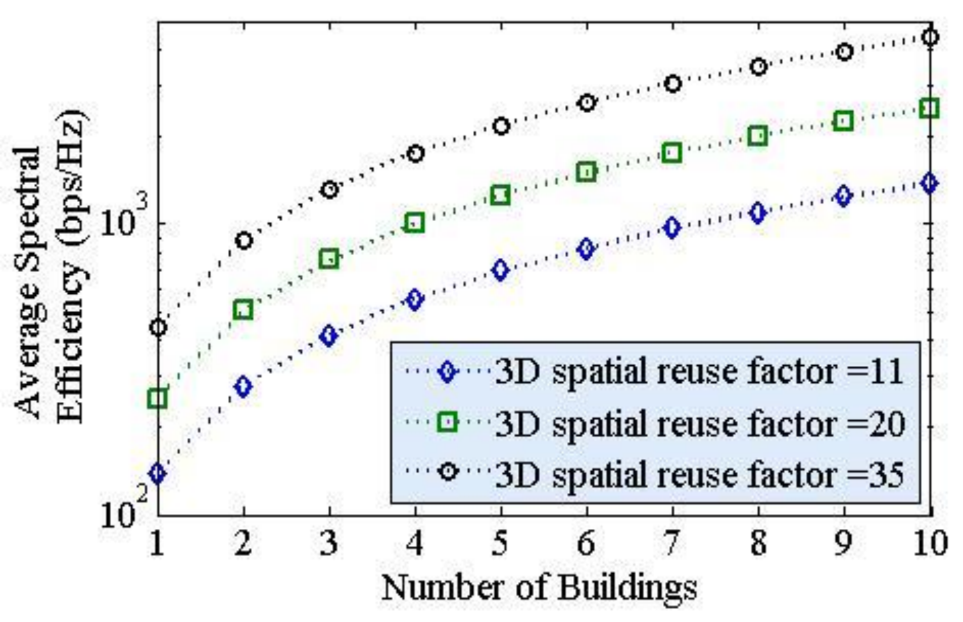

Figure 13. Average SE response for numerous 3D spatial reuse factors per building with a variation in the number of buildings of SBSs (i.e., hRF) [1].

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.

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*.

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.

References

1. R. K. Saha, “3D Spatial Reuse of Multi-Millimeter-Wave Spectra by Ultra-Dense In-Building Small Cells for Spectral and Energy Efficiencies of Future 6G Mobile Networks,” Energies, vol. 13, no. 7, art. no. 1748, 2020. doi: 10.3390/EN13071748.
2. R. K. Saha and C. Aswakul, “A Tractable Analytical Model for Interference Characterization and Minimum Distance Enforcement to Reuse Resources in Three-Dimensional In-Building Dense Small Cell Networks,” Int. J. Commun. Syst., vol. 30, no. 11, pp. 95-118, July 2017, doi: 10.1002/DAC.3240.
3. R. K. Saha, “A Tactic for Architectural Exploitation of Indoor Small Cells for Dynamic Spectrum Sharing in 5G,” IEEE Access, vol. 8, pp. 15056-15071, January 2020, doi: 10.1109/ACCESS.2020.2966230.
4. H. Kamal, M. Coupechoux, and P. Godlewski, “Inter-Operator Spectrum Sharing for Cellular Networks Using Game Theory,” Proc. 2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications, Tokyo, 2009, pp. 425-429.
5. S. K. Joshi, K. B. S. Manosha, M. Codreanu, and M. Latva-aho, “Dynamic Inter-Operator Spectrum Sharing via Lyapunov Optimization,” IEEE Trans. Wirel. Commun., vol. 16, no. 10, pp. 6365-6381, Oct. 2017, doi: 10.1109/TWC.2017.2722999.
6. R. K. Saha, “Interweave Shared-Use Model for Dynamic Spectrum Access in Millimeter-Wave Mobile Systems for 6G,” Proc. 2020 IEEE 92nd Vehicular Technology Conference (VTC2020- Fall), Victoria, BC, Canada, 18-Nov.-16 Dec., 2020, pp. 1-6, doi: 10.1109/VTC2020- Fall49728.2020.9348671.
7. R. K. Saha, “Underlay Cognitive Radio Millimeter-Wave Spectrum Access for In-Building Dense Small Cells in Multi-Operator Environments Toward 6G,” Proc. IEEE 23rd International Symposium on Wireless Personal Multimedia Communications (WPMC), Okayama, Japan, 19-26 Oct. 2020, pp. 1-6, doi: 10.1109/WPMC50192.2020.9309471.
8. M. G. Khoshkholgh, K. Navaie, and H. Yanikomeroglu, “Interference Management in Underlay Spectrum Sharing Using Indirect Power Control Signalling,” IEEE Trans. Wirel. Commun., vol. 12, no. 7, pp. 3264-3277, July 2013, doi: 10.1109/TWC.2013.052813121110.
9. W. Liang, K. D. Wang, J. Shi, L. Li, and G. K. Karagiannidis, “Distributed Sequential Coalition Formation Algorithm for Spectrum Allocation in Underlay Cognitive Radio Networks,” IEEE Access, vol. 7, pp. 56803-56816, 2019, doi: 10.1109/ACCESS.2019.2910720.
10. R. K. Saha, “Hybrid Interweave-Underlay Millimeter-Wave Spectrum Access in Multi-Operator Cognitive Radio Networks Toward 6G,” Proc. Fifteenth International Conference on Systems and Networks Communications (ICSNC), Porto, Portugal, 18-22 Oct. 2020, pp. 42-48.
11. A. U. Khan et al., “HBLP: A Hybrid Underlay-Interweave Mode CRN for the Future 5G-based Internet of Things,” IEEE Access, vol. 8, pp. 63403-63420, 2020, doi: 10.1109/ACCESS.2020.2981413.
12. P. Zuo, T. Peng, W. Linghu, and W. Wang, “Optimal Resource Allocation for Hybrid Interweave-Underlay Cognitive Satcom Uplink,” Proc. The 2018 IEEE Wireless Communications and Networking Conference (WCNC), Barcelona, Spain, April 2018, pp. 1-6.
13. F. Mehmeti and T. Spyropoulos, “Performance Analysis, Comparison, and Optimization of Interweave and Underlay Spectrum Access in Cognitive Radio Networks,” IEEE Trans. Veh. Technol., vol. 67, pp. 7143-7157, Aug. 2018, doi: 10.1109/TVT.2018.2828090.
14. R. K. Saha, “A Technique for Massive Spectrum Sharing with Ultra-dense In-building Small Cells in 5G era,” Proc. IEEE 90th Veh. Technol. Conf. (VTC-Fall), Honolulu, HI, USA, Sep. 2019, pp. 1-7.
15. M. R. Hassan, G. C. Karmakar, J. Kamruzzaman, and B. Srinivasan, “Exclusive Use Spectrum Access Trading Models in Cognitive Radio Networks: A Survey,” IEEE Commun. Surv. Tuts., vol. 19, no. 4, pp. 2192-2231, Fourth quarter 2017, doi: 10.1109/COMST.2017.2725960.

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Thank You …