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In-Building Small Cell Networks: Achieving High Capacity Indoors

A Tutorial

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

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Biography

RONY KUMER SAHA has been working as a Research Engineer (**Postdoctoral Fellow**) with the Radio and Spectrum Laboratory, **KDDI Research, Inc., Japan** since 2017. He received the **Ph.D.** degree in electrical engineering from **Chulalongkorn University, Thailand** and the **M.Eng.** degree in information and communications technologies from **Asian Institute of Technology, Thailand**, in 2017 and 2011, respectively.

From September 2013 to July 2014, he was with East West University, Bangladesh. Before that he worked as a Lecturer and later promoted to an **Assistant Professor** with American International University-Bangladesh (AIUB), Bangladesh, from January 2005 to August 2013. He has research experiences on mobile wireless communications in universities and industries for about **11 years**. He has authored about **60 peer-reviewed**, reputed, and recognized international **journals** (such as IEEE Access, International Journal of Communication Systems (Wiley), Mobile Information Systems (Hindawi), Wireless Communications and Mobile Computing (Wiley/Hindawi), Sensors (MDPI), Energies (MDPI), and IEEJ Transactions on Electrical and Electronic Engineering (Wiley) and **conferences** (IEEE ICC, IEEE GLOBECOM, IEEE PIMRC, IEEE VTC, IEEE DySPAN, WPMC, ICSNC, ICN, and ECTI-CON) papers. He received the **Best Paper Award** in IARIA ICSNC 2020, Portugal and the **Highest Evaluation Score (Postdoctoral Fellow)** for **four** consecutive fiscal-half years (2019-2020) at KDDI Research, Inc., Japan. He also filed an international **patent**. His current research interests include 5G and beyond ultra-dense HetNets, spectrum sharing, policy, and management in multiple communication systems, and millimeter-wave communications.

Dr. Saha has been serving as an **Associate Editor** of the Engineering Journal, Thailand since 2019. He is currently serving as a **Steering Committee Member** of IARIA ICSNC 2021. 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, as well as the 2021 IARIA ICNS. 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, NJ, USA, for the session Spectrum Sharing in 5G. Dr. Saha also served as a **Reviewer** for a number of 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).

Tutorial Presenter

Research Interests

- 5G NR-U: 5G New Radio on Unlicensed Bands
- Dynamic spectrum sharing and policy for 5G and beyond mobile networks
- Millimeter wave communications
- 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

Tutorial

Outline

- Introduction to Small Cells
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- In-building Signal Propagation Characteristics
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Introduction: Definition

A cellular radio access node that provides small coverage (typically in the order of 10 meters) at a 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 an usual scenario, to provide a good signal quality.

Note that, in this tutorial, we limit the discussion to the use of small cells under in-building scenarios (Figure 1). Also, we use the terms "small cell" and "femtocell" interchangeably.

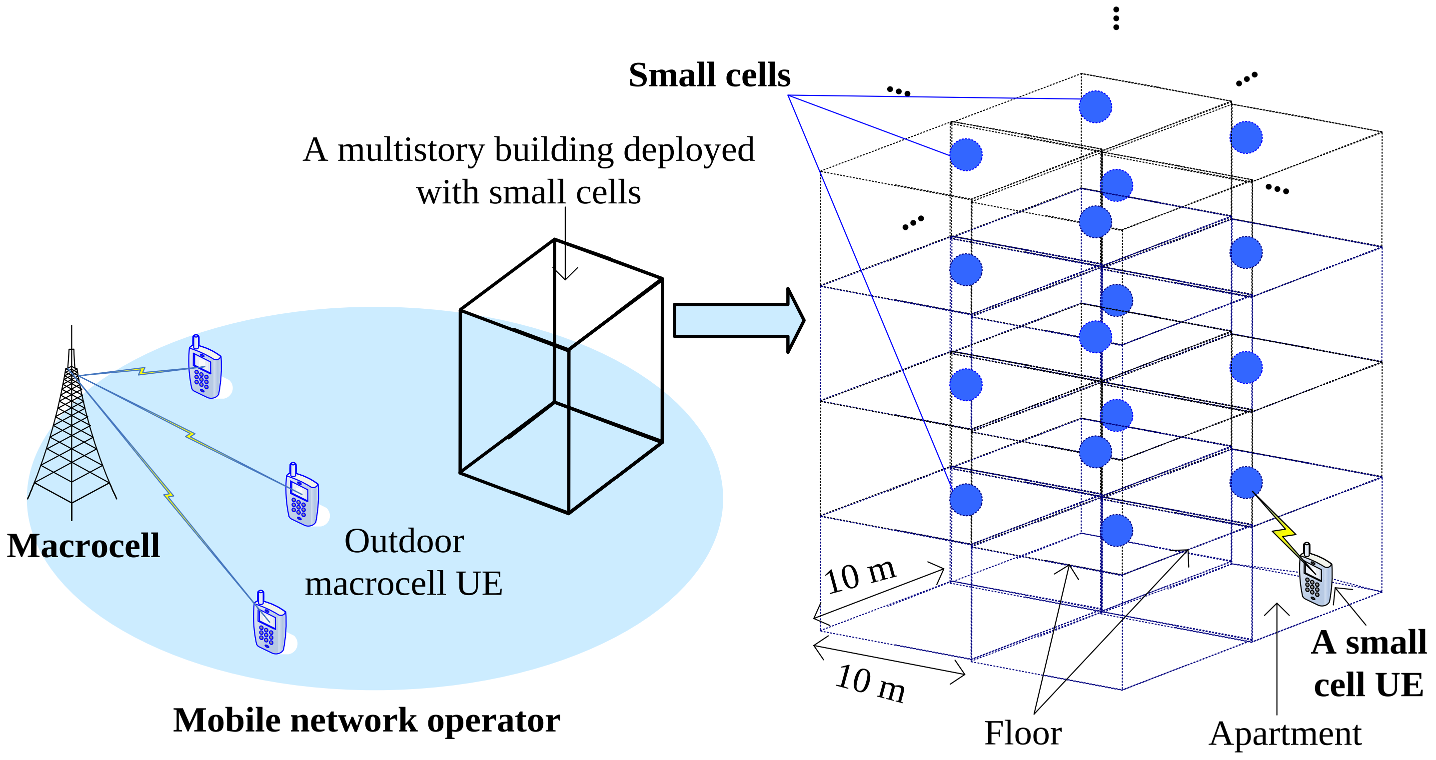

Figure 1. In-building small cell networks

Introduction: In-Building Small Cell Network Densification

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 of how to address indoor high data rate and enormous traffic 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 the high data rate. Besides, Small Cell BSs (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. This necessitates capturing 3-Dimensional (3D) effects, e.g. floor penetration loss, on indoor signal propagations by considering the height of a building.

Introduction: Millimeter-Wave Spectrum

The millimeter-wave (mmWave) spectrum bands are considered as promising candidate bands to address the high capacity demand of next-generation mobile systems such as Fifth-Generation (5G) and beyond systems in dense urban multistory buildings.

Besides, Mobile Network Operators (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.

Introduction: Three-Dimensional (3D) Spatial Spectrum Reuse Indoors

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 in order 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.

Introduction: 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 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 been 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 has been found to be more effective.

In 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 to realizing numerous DSS techniques. In this regard, to avoid Co-Channel Interference (CCI), when sharing the licensed spectrum of one MNO to another, Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) can be employed to small cells to allow time orthogonality while serving traffic of the respective MNO.

Introduction: 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 in 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, 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 allows sharing the licensed spectrum of one MNO with another to increase its effective spectrum bandwidth to serve high data rates and capacity.

Small Cell Access Mechanism

Femtocells are considered as 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 (Figure 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 to the corresponding femtocell.

However, when some of resources are reserved for the registered home users and the rest is assured for other users, such deployment approach is called hybrid access.

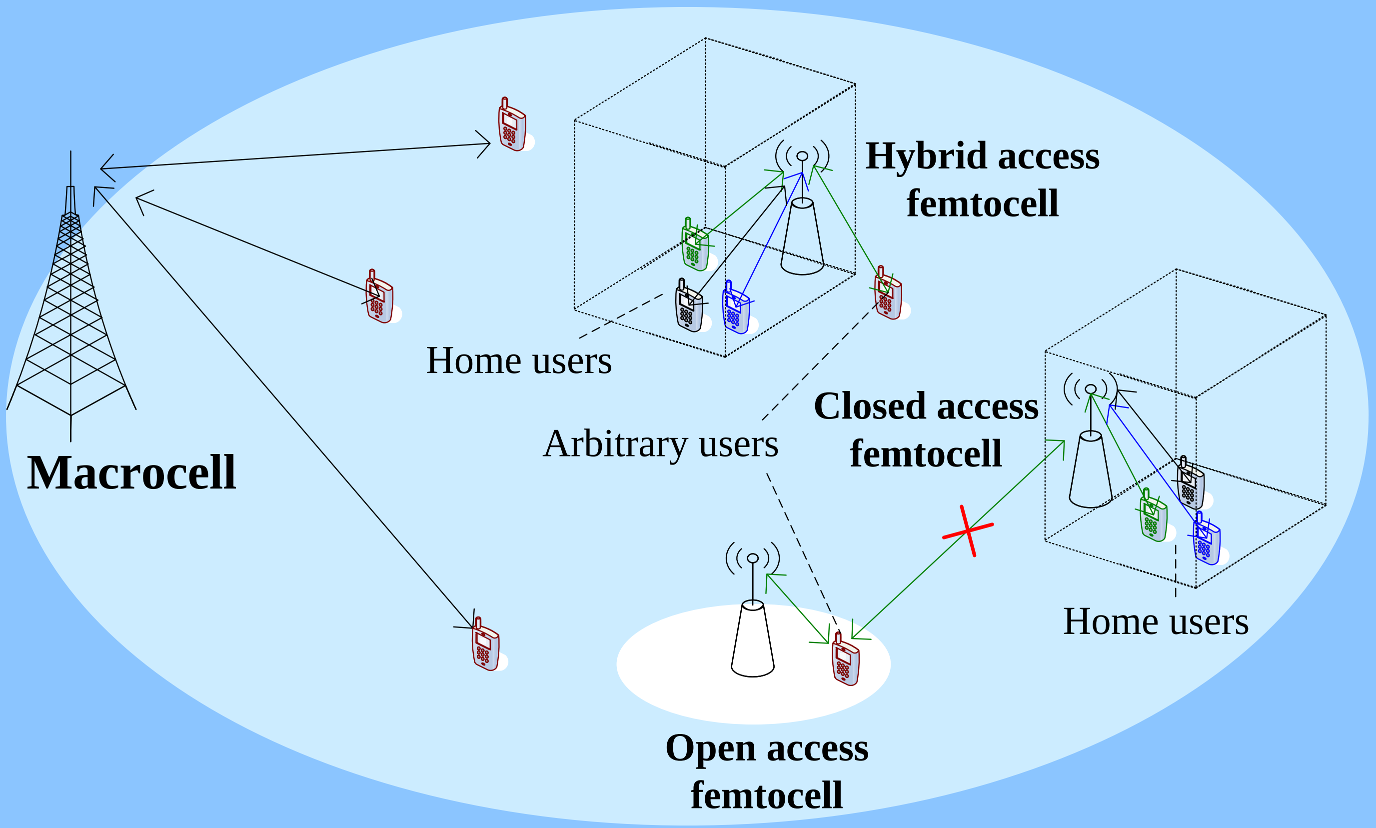

Figure 2. Approaches to access a small cell (i.e., femtocell)

Small Cells

Small Cell Access Mechanism

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However, when some of resources are reserved for the registered home users and the rest is assured for other users, such deployment approach is called hybrid access.

- 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 prefers to 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.

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 Line-Of-Sight (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 that in 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.

In-building Signal Propagation Characteristics (1)

Path Loss

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.

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

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 representing largescale signal variation about the mean path loss due to shadowing.

LOS
Fading

In-building Signal Propagation Characteristics (2)

LOS

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.

Large and Small Scale Fading Effect

For the similar structure for all apartments within a multi-floor building, all indoor channels can be assumed to experience the similar shadowing effect. Further, the small-scale channel fading occurs due to Doppler spread and delay spread effects on the channel.

However, due to 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.

Penetration Loss

In-building Signal Propagation Characteristics (3)

Floor 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 [1]
- Using [9] and fitting the curve for a concrete block in [7], according to [1], the floor penetration loss in the 28 GHz mmWave spectrum is 55 dB for the first floor (Table I)

Penetration Loss

In-building Signal Propagation Characteristics (4)

Internal and External Wall Penetration Loss

- Internal and external wall penetration loss play a significant role. Table I shows for penetration losses for 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 [11]
- 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 increases accordingly.

TABLE I. FLOOR PENETRATION LOSS IN THE 28 GHZ MMWAVE SPECTRUM BAND [7-10].

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

In-building Signal Propagation Characteristics (5)

Indoor Propagation Modeling

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

- Approach 01: consider nearby buildings' reflection effects, particularly in urban environments where buildings are very close in distance to one another;
- Approach 02: Not to consider nearby buildings' reflection effects 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.

Background (1)

Received signal capacity at a receiver is a function of the distance from the transmitter and available spectrum bandwidth.

- (a) The lower the distance and/or (b) higher the spectrum, the better the received signal capacity.
- How can we achieve both?
- For (a), Reduce the cell size so that transmitter and receiver are as close in distance as possible (Figure 3).
- For (b) Reduction in cell coverage allows reusing the same spectrum spatially

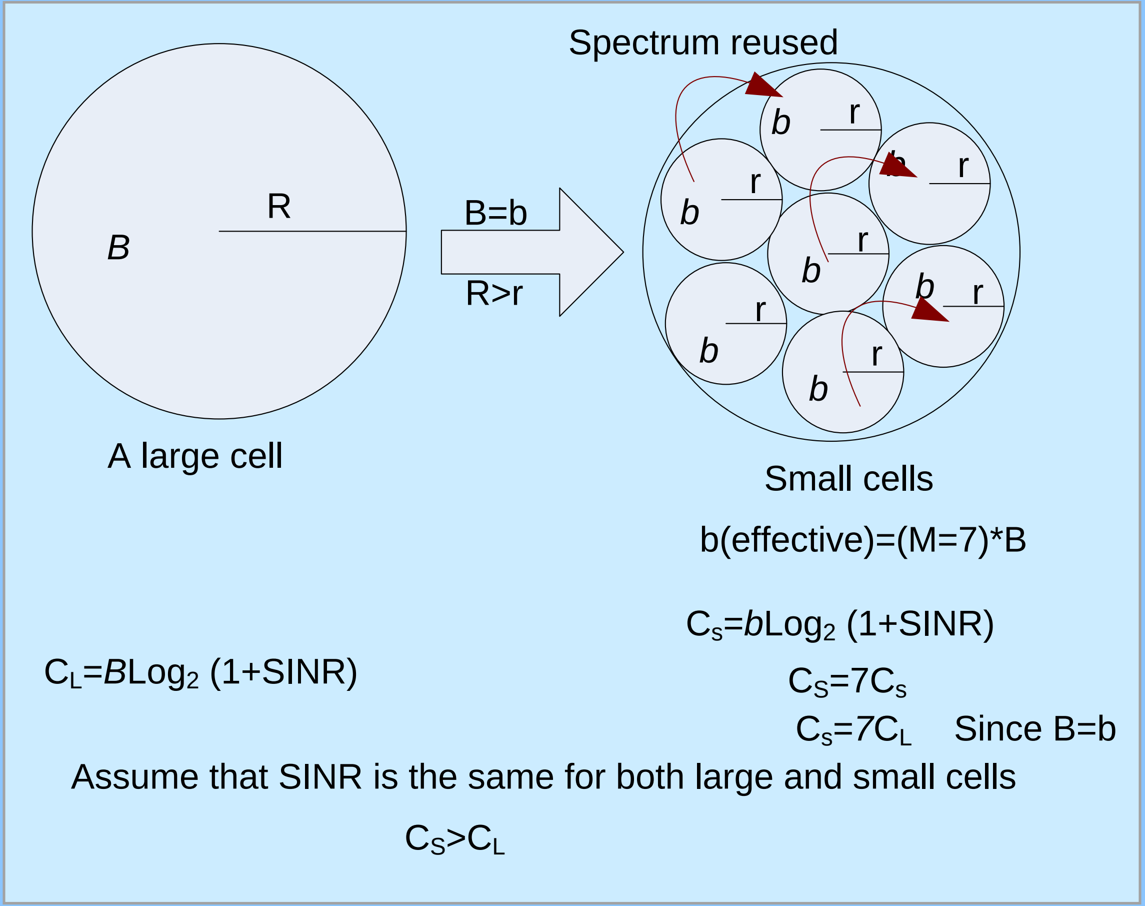


Figure 3. Formation of small cells from a large macrocell.

Since C_L and C_S are proportional to the Signal-to-Interference-plus-Noise-Ratio (SINR), the achievable capacity C_S improves by the factor m=7

Background (2)

Shannon's Capacity Formula

Spectrum reuse factor

Received desired signal power

Achievable Capacity $$C_L = \Phi \times B \, \mathrm{Log}_2 \left(1 + \left(\frac{P_\mathrm{r}}{N + I_\mathrm{T}} \right) \right) \quad (1)$$

Available bandwidth

Noise

Received total interference signal power

Background (3)

Using Shannon's capacity formula in (1), network capacity can be improved mainly by the following three directions:

- Spectrum accessibility
- Spectral efficiency improvement
- Network densification

which are shown in a network capacity improvement triangle in Figure 4 along three directions. Corresponding enabling technologies to improve network capacity indoors using small cells deployed in a building are also shown along each direction.

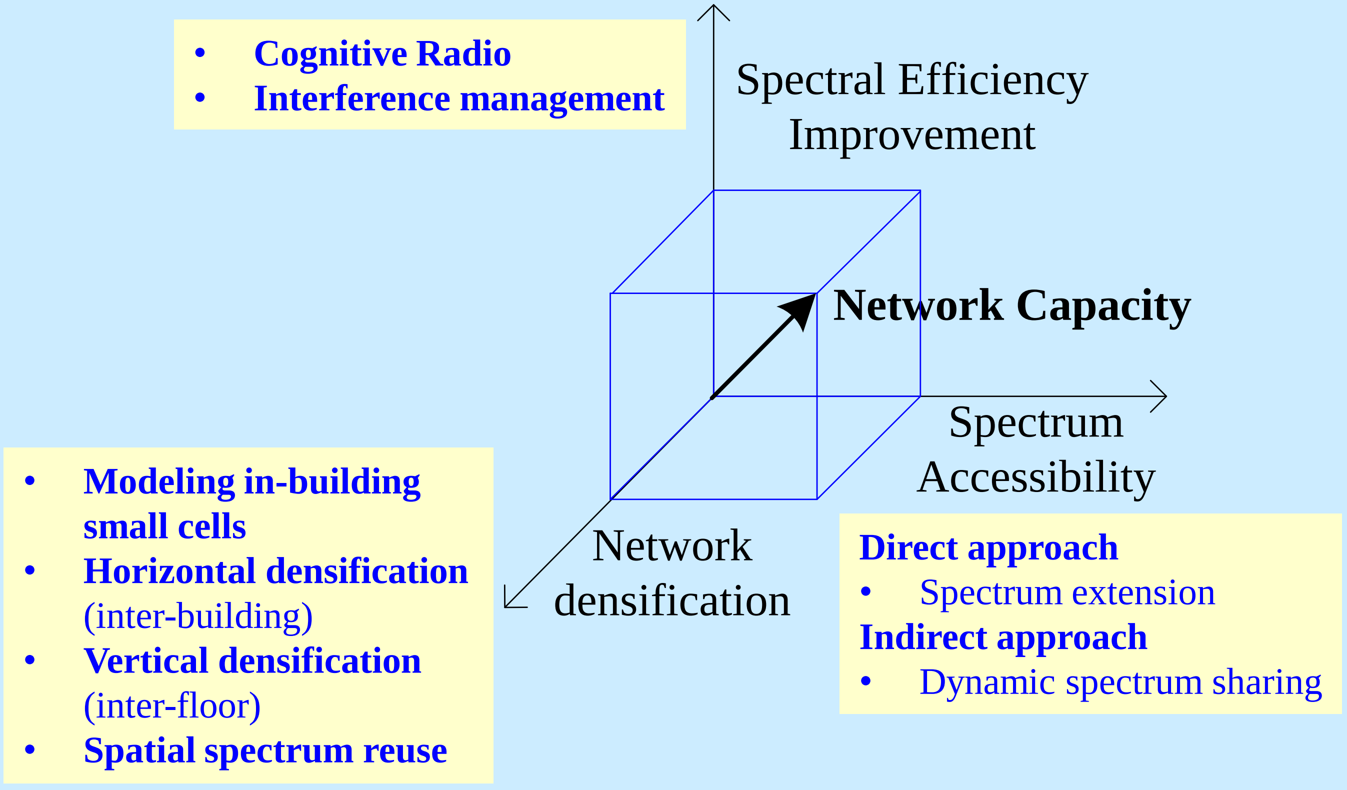


Figure 4. Network capacity improvement triangle.

In this tutorial, in-building small cells are exploited along these three dimensions to achieve high capacity and data rates demands of existing and upcoming mobile networks.

Direct Approach

Available spectrum for an MNO can be increased in two major ways as follows:

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

In direct approach, new licensed spectrum can be added directly to a mobile system using techniques such as Carrier Aggregation (Figure 5), be it contiguous or noncontiguous.

The traditional Direct approaches in order to extend spectrum are no more effective due to the scarcity of radio spectrum availability, particularly below 3 GHz [12], as well as a huge cost of licensing spectrum. This ask for exploiting indirect approaches to address ever-increasing indoor high data rates and capacity demands for MNOs.

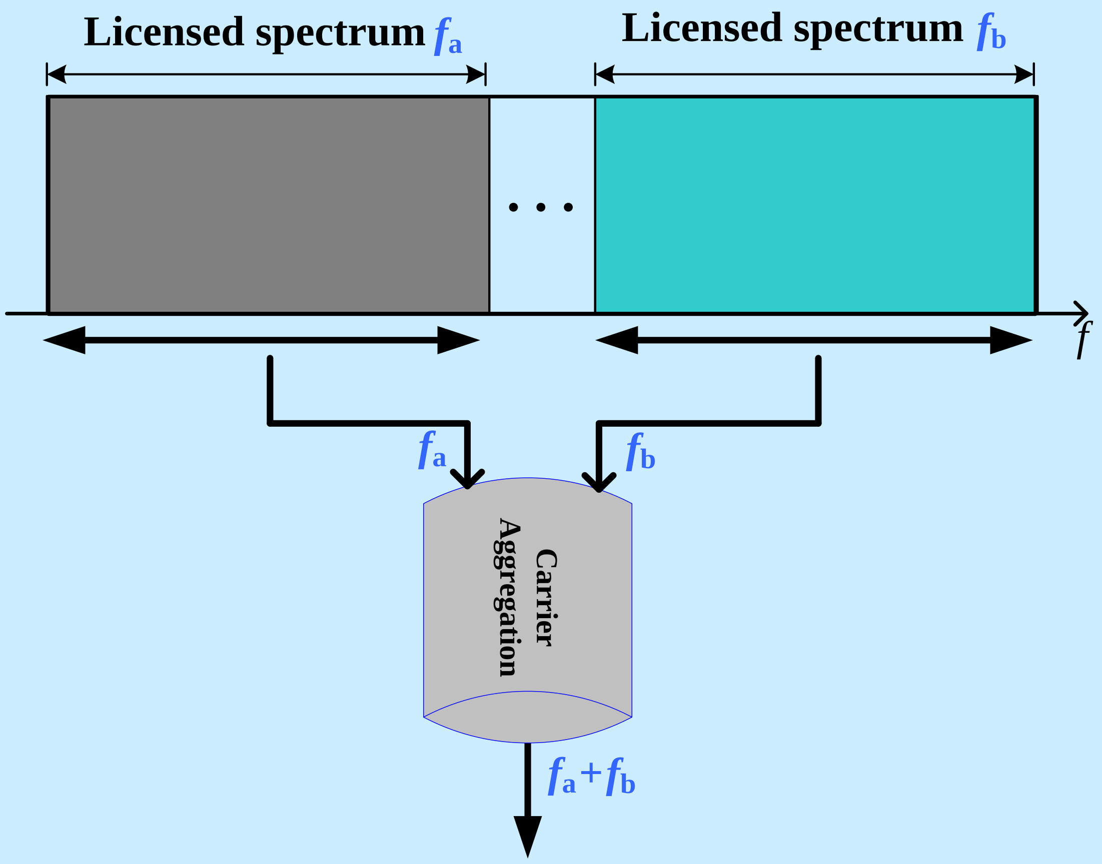


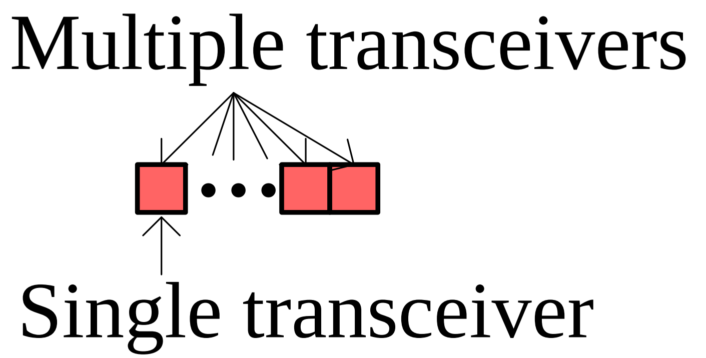
Figure 5. Carrier Aggregation technique.

Indirect Approach: Dynamic Spectrum Sharing

In 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. Literally, such an approach can be termed as Dynamic Spectrum Sharing (DSS).

Small cells indoors can play a crucial role to DSS. Based on the number of physical transceivers as well as the number, amount, and characteristics of operating spectrums of an SBS, several small cell base station architectures can be realized to address numerous DSS approaches [3].

Note: The necessity of multiple transceivers per SBS is justified by the fact that when two or more systems operate at spectrums with diverse signal propagation characteristics would need different transceiver features (e.g., different filter characteristics).



Spectrum Accessibility

In-Building Small Cell Base Station Architecture for DSS

Let xm denotes the maximum number of MNOs such that $x \in \boldsymbol{x} = \{1, 2, ..., \text{xm}\}$ denotes a set of MNOs assigned with the licensed spectrums $f_x \in \boldsymbol{f_x} = \{f_1, f_2, ..., f_{\text{xm}}\}$.

Let $F_{l,x} \in \boldsymbol{F_{l,x}} = \{F_{l,1}, F_{l,2}, ..., F_{l,\text{xm}}\}$ denote a set of licensed spectrums of other systems than any mobile system, e.g. satellite systems and Fixed Wireless Access (FWA).

Let $F_{ul,x} \in \boldsymbol{F_{ul,x}} = \{F_{ul,1}, F_{ul,2}, ..., F_{ul,\text{xm}}\}$ denote a set of unlicensed spectrums, e.g. 60-GHz, 5-GHz, and 2.4 GHz spectrums.

Let f_2 be the spectrum of the MBS

Spectrum Accessibility

In-Building Small Cell Base Station Architecture for DSS

Type 1: single-transceiver single-band enabled SBSs operating in the licensed spectrums of homogeneous systems (Figure 6(a)).

In this type of SBS, both the MBS and an SBS operate at their own MNO's spectrum subject to the interference management policy set by the MNO.

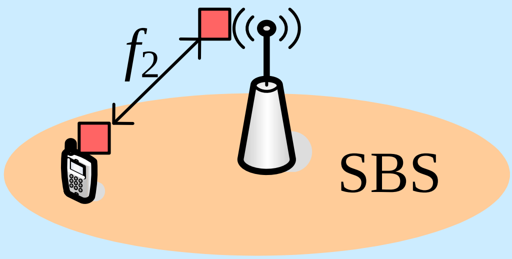


Figure 6 (a) Type 1

Example DSS approaches: This Type of SBS can be used for the Co-Channel Shared Access (CSA) between an MBS and in-building SBSs of an MNO using the eICIC technique.

Type 02: single-transceiver single-band enabled SBSs operating in the licensed spectrums of heterogeneous systems (Figure 6(b)).

The MBS and an in-building SBS of an MNO operate at different frequencies.

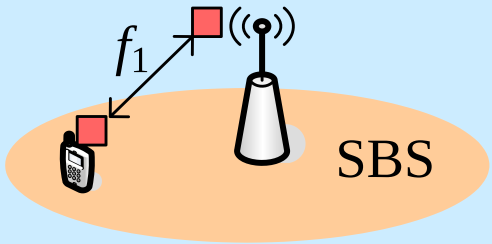


Figure 6 (b) Type 2

Example DSS approaches: This Type of SBS can be used for Licensed Shared Access (LSA) for sharing the licensed spectrum of a heterogeneous system with in-building SBSs of an MNO.

In-Building Small Cell Base Station Architecture for DSS

Type 03: single-transceiver single-band enabled SBSs operating in the unlicensed spectrums of heterogeneous systems (Figure 6(c)).

In-building SBSs of an MNO operate in an unlicensed heterogeneous spectrum band.

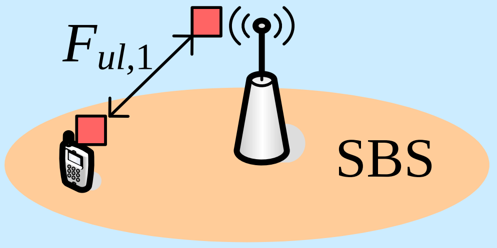


Figure 6 (c) Type 3

Example DSS approaches: used for the unlicensed shared access (ULA) to operate in-building SBSs of an MNO at an unlicensed heterogeneous spectrum band.

Type 04: single-transceiver multiband enabled SBSs operating in the licensed spectrums of homogeneous systems (Figure 6(d)).

An in-building SBS operates in the spectrums of multiple MNOs in the same region using a single-transceiver by employing techniques such as carrier aggregation.

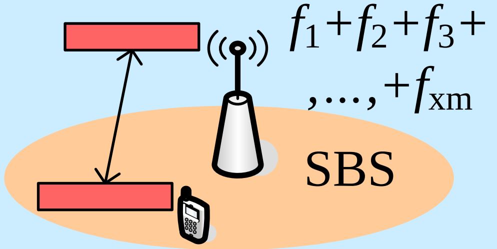


Figure 6 (d) Type 4

Example DSS approaches: Authorized shared access (ASA) can be realized subject to the interference management among MNOs.

In-Building Small Cell Base Station Architecture for DSS

Type 05: multi-transceiver multiband enabled SBSs operating in the licensed spectrums of homogeneous systems (Figure 6(e)).

Multiple transceivers are needed due to the diverse signal propagation characteristics at the operating spectrums of MNOs.

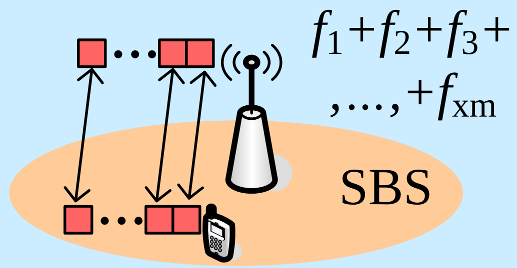


Figure 6(e) Type 5

Example DSS approaches: Co-primary shared access such as spectrum pooling and spectrum renting can be realized.

Type 06: multi-transceiver multiband enabled SBSs operating in the licensed spectrums of heterogeneous systems (Figure 6(f)).

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.

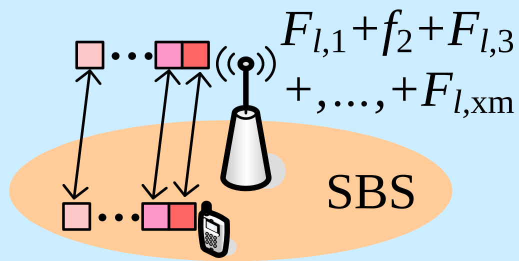


Figure 6(f) Type 6

Example DSS approaches: CSA can be realized with one transceiver and LSA can be realized with another transceiver of the SBS.

In-Building Small Cell Base Station Architecture for DSS

Type 07: multi-transceiver multiband enabled SBSs operating in the unlicensed spectrums of heterogeneous systems (Figure 6(g)).

An SBS operates at the spectrum of its own MNO as well as at the unlicensed spectrum of a heterogeneous system using multiple transceivers.

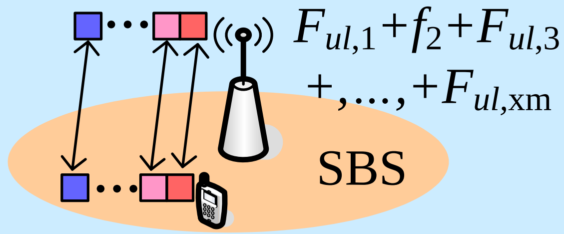


Figure 6 (g) Type 7

Example DSS approaches: CSA can be realized with one transceiver and LAA can be realized with another transceiver of the SBS.

Type 08: multi-transceiver multiband enabled SBSs operating in the licensed and unlicensed spectrums of heterogeneous systems – **option 1** (Figure 6(h)).

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.

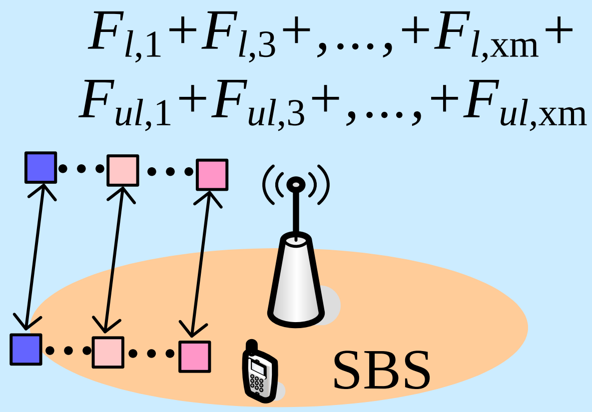


Figure 6 (h) Type 8

Example DSS approaches: LSA can be realized with one transceiver, whereas LSA with another transceiver.

In-Building Small Cell Base Station Architecture for DSS

Type 09: multi-transceiver multiband enabled SBSs operating in the licensed and unlicensed spectrums – **option 2** (Figure 6(i)).

One of the transceivers of an SBS operates at 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.

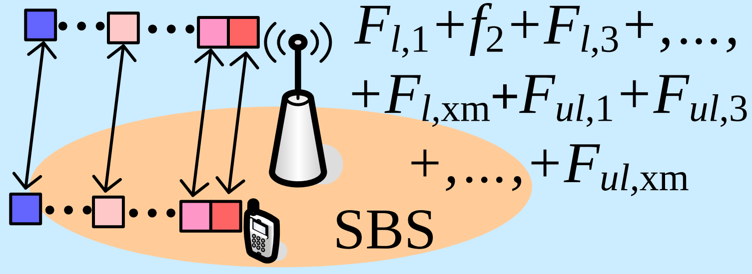


Figure 6 (i) Type 9

Example DSS approaches: 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.

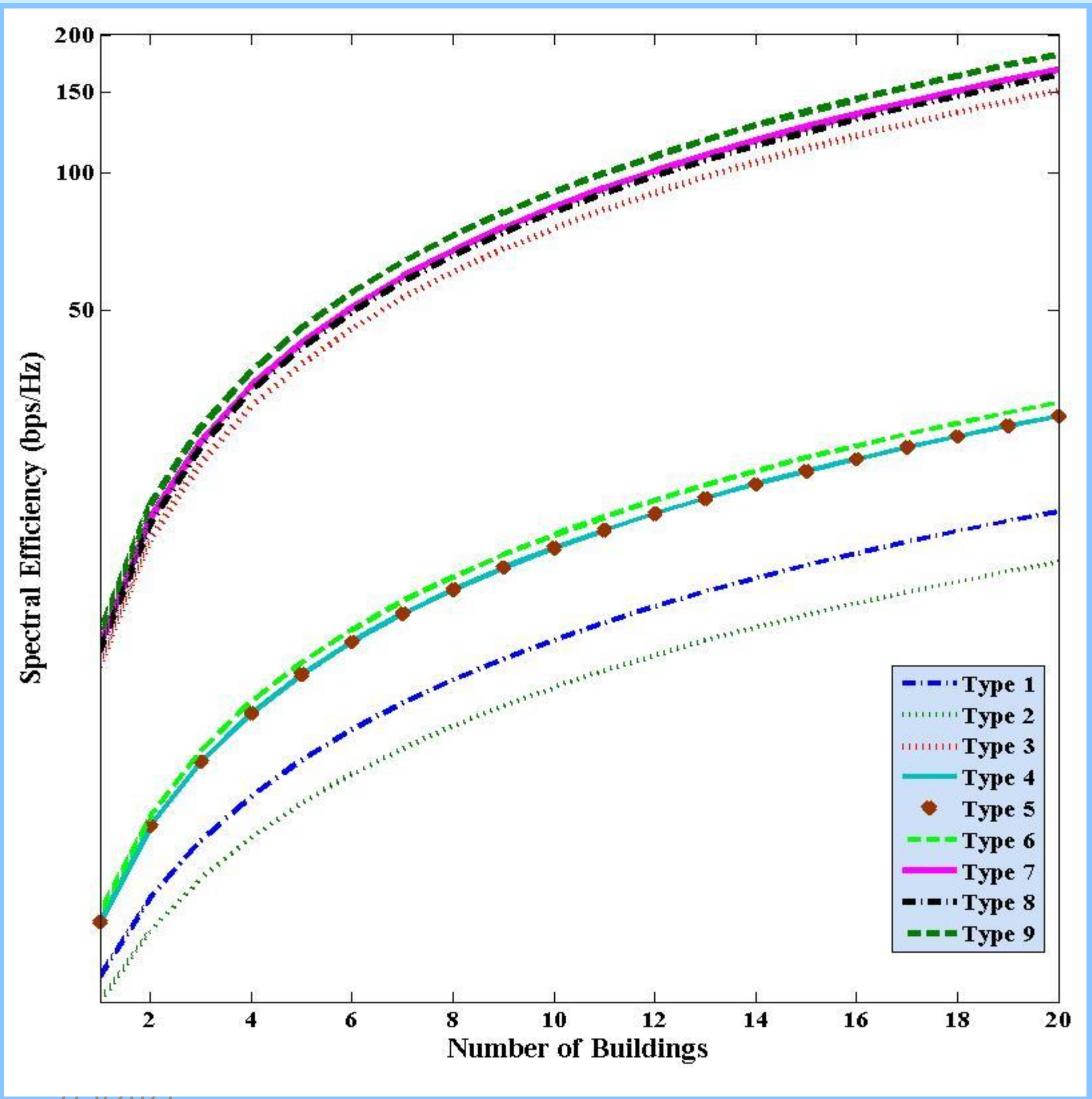
All the realized DSS approaches by exploiting an SBS architecture is shown in Table II.

TABLE II. REALIZED DSS

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

In-Building Small Cell Base Station Architecture for DSS

Default parameters and assumptions can be found in [3].



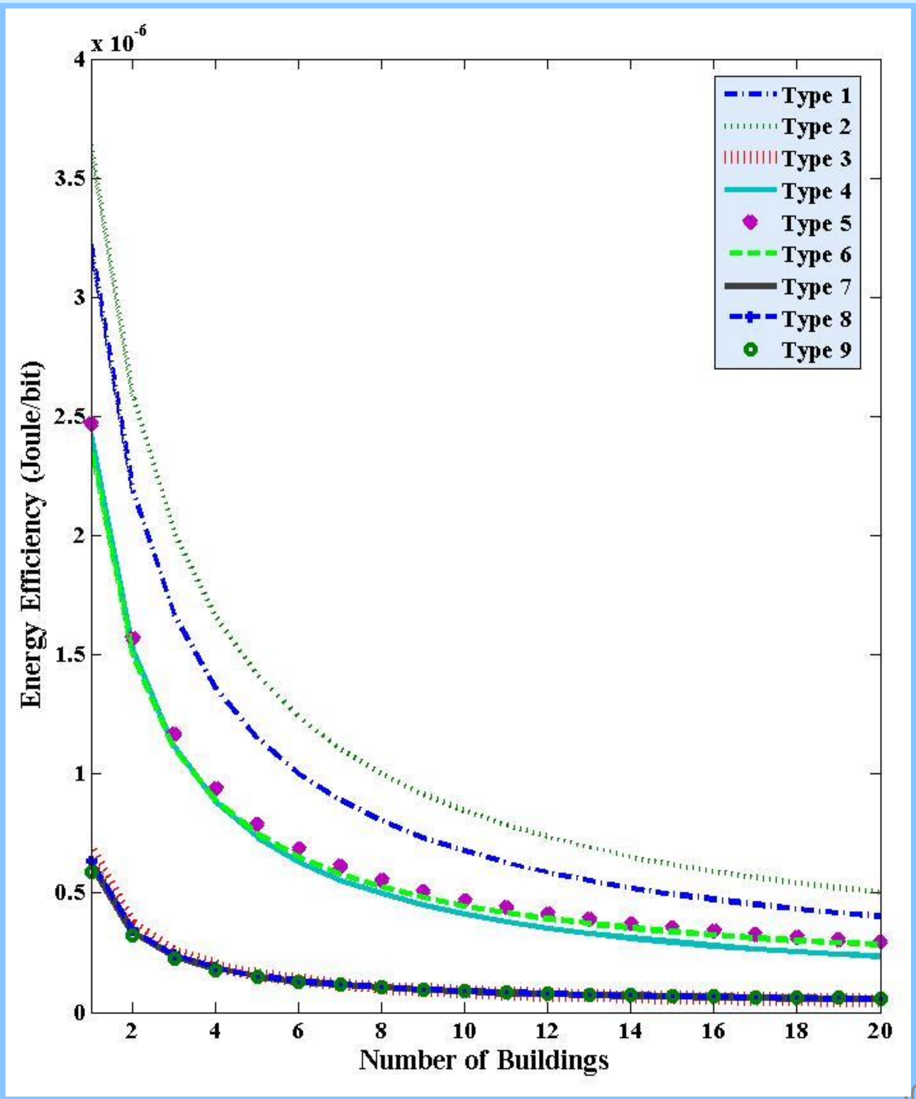


Figure 7. Spectral Efficiency (SE) and Energy Efficiency (EE) responses of numerous SBS architectures.

Enhanced Intercell Interference Coordination

Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) is used to avoid CCI when sharing the licensed spectrum of homogeneous/ heterogeneous system as given below. For unlicensed band, no CCI is considered.

Figure 8 shows an illustration of the ABS based eICIC technique, which is applied to any transceiver of an SBS depending on its operating spectrum.

"An SBS architecture can be configured such that it can operate only during non-ABSs per ABS Pattern Period (APP)."

Note that, an ABS is a Transmission Time Interval (TTI) during which no data signal is transmitted except some control signals such as broadcast and synchronization signals.

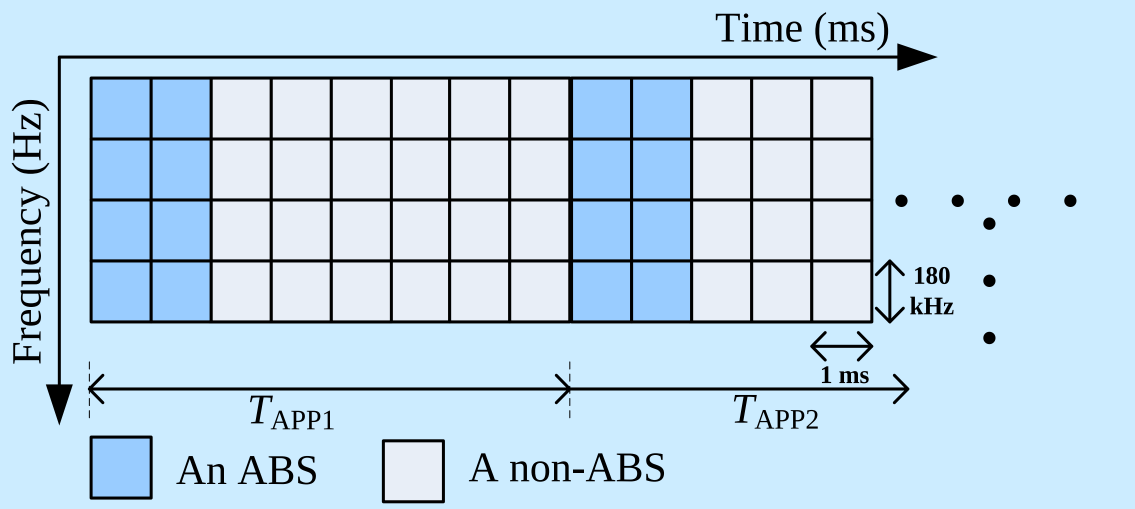


Figure 8. An illustration of the ABS based eICIC technique.

Hence, an SBS can be scheduled at the same frequency of another system only during non-ABSs per APP to transmit its user data while the other shared-frequency system mutes transmitting its user data to avoid co-channel interference.

In-Building Small Cell Base Station Architecture for DSS

In [3], the following has been observed from Figure 7, that the network capacity and SE can be improved by exploiting an SBS architecture to allow more spectrum to be available using DSS technique.

- 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 due to the fact that 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 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.

In-Building Small Cell Base Station Architecture for DSS

Like SE, similar responses can be observed for EE, 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 is not considerable.

This is because of the fact that 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.

Network Densification

Modeling In-building Small cells: Intra-floor Interference Modeling (Horizontal Densification)

Consider a 3D multi-floor building that consists of a number of 2D floors, and each floor consists of a number of square-grid apartments with each side length *a*=10m. A cluster of SBSs is deployed in apartments of the building such that each apartment has one SBS.

- Figure 9 shows intra-floor CCI modeling where a link between a Co-channel SBS (cSBS) and serving small cell UE (sSU) is termed as CCI link, and the one between sSU and its sSBS is termed as desired link.
- An illustration of an example aggregate interference effect of all cSBSs at sSU of an sSBS is shown in Figure 9 [2].
- The region up to which the aggregate interference is significant enough so that it exceeds a maximum allowable aggregate interference at sSU is termed as the Region of Exclusion (RoE) for reusing the same resources of sSBS in any SBSs within RoE.
- Hence, RoE in Figure 9 is up to tier-2 and is shown in yellow color.

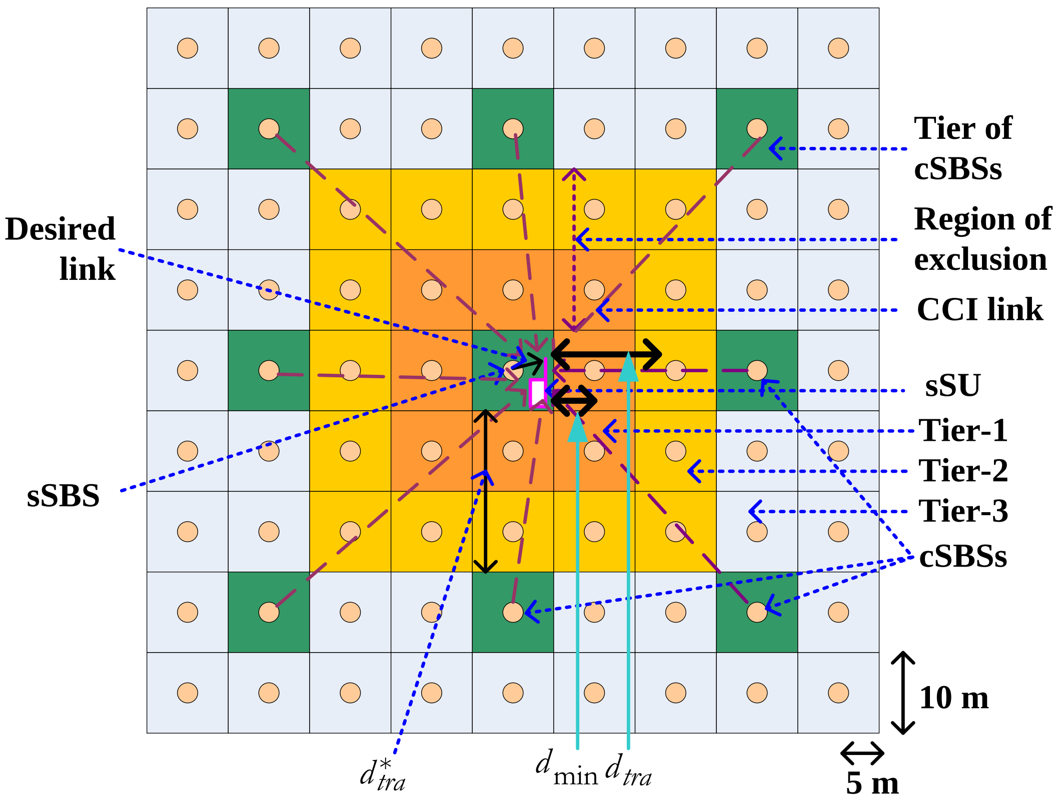


Figure 9. Intra-floor CCI and RoE modeling [2].

Modeling In-building Small cells: Inter-floor Interference Modeling (Vertical Densification)

We assume that all FCBSs are located on the ceilings and centers of all apartments.

- 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 [2].
- With this concern, inter-floor interference modeling can be performed as shown in Figure 10.

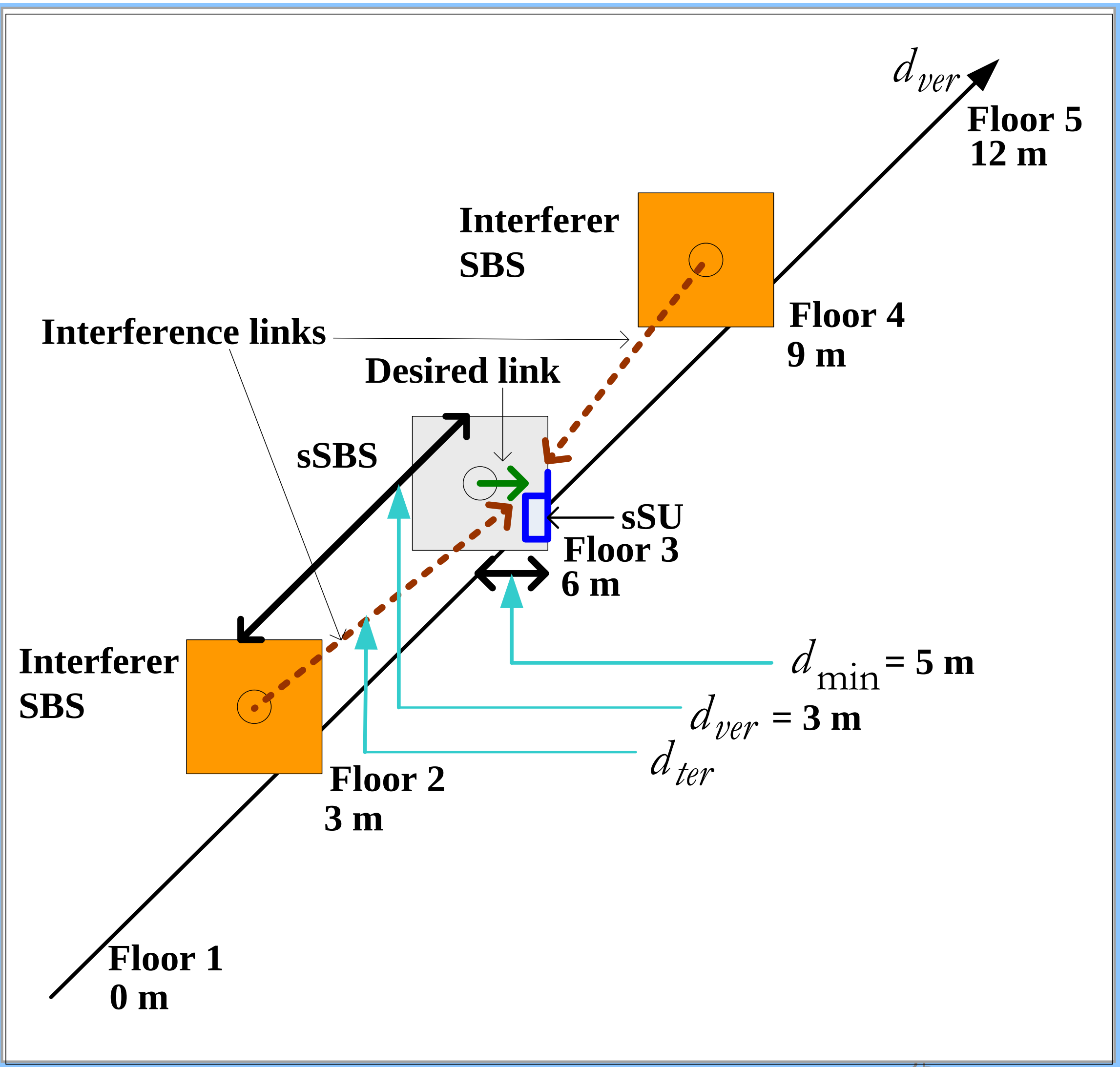


Figure 10. Inter-floor interference modeling and architecture [2].

Modeling In-building Small cells: 3D In-building Interference Modeling (3D Densification)

Figure 11 shows a detail diagram of 3D in-building small cell interference modeling combining the effects of intra-floor and inter-floor CCIs [2].

- If the reuse of resources is performed on an intermediate floor, two cSBSs need to be considered of which 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.

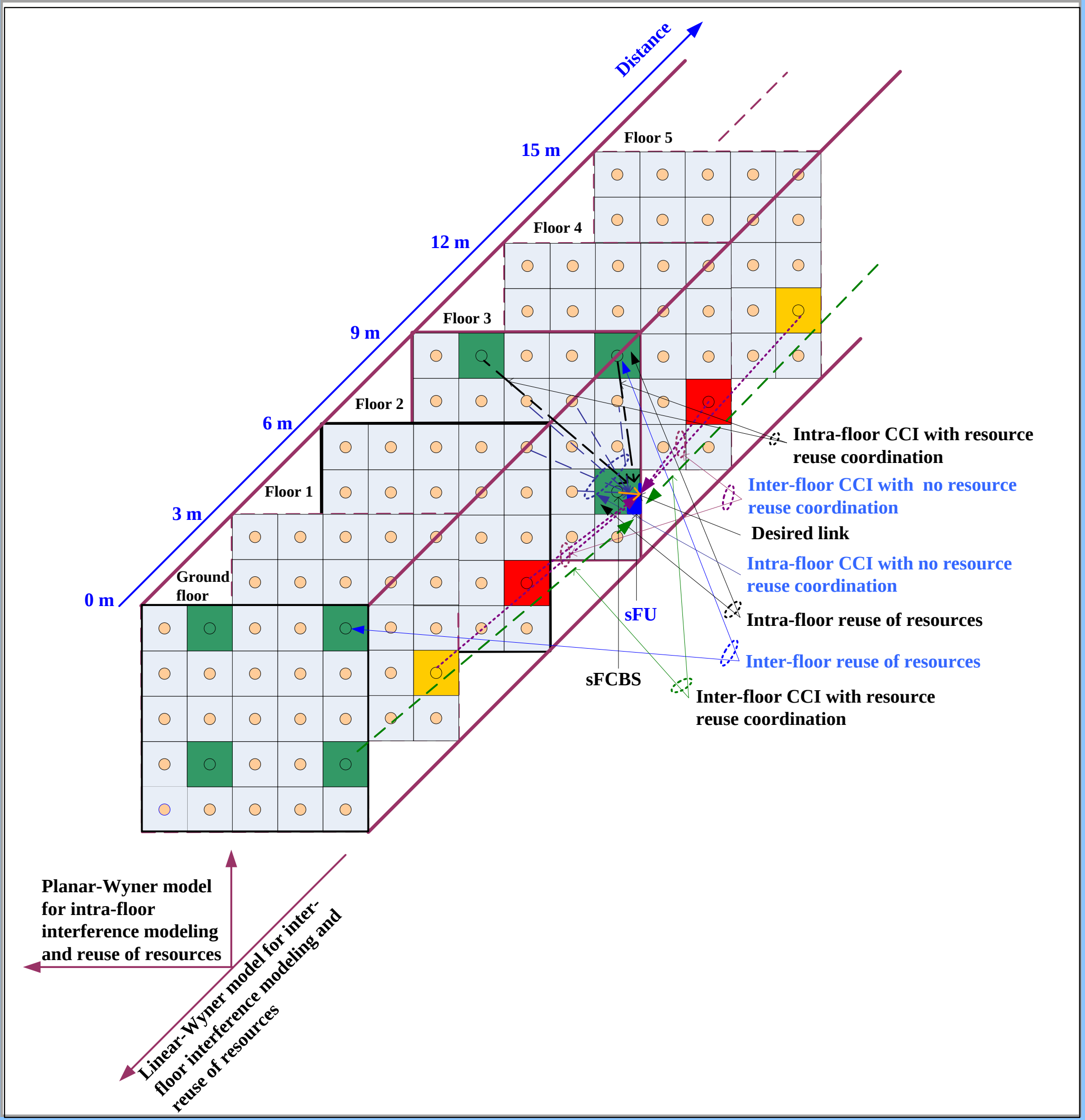


Figure 11. A detail 3D in-building intra-and inter-floor interferences model and architecture for reusing resources in SBSs [2].

Modeling In-building Small Cells: Mathematical Analysis

The normalized value of intra-floor interference power at an arbitrary distance d_{tra} from a cSBS at sSU is given by [2]

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

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 [2]

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

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. 11, the total aggregate interference power at sSU is given by

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

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

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. Then, the following must satisfy.

$$\alpha_{agg,ter}+\alpha_{agg,tra}\leq\alpha_{thr,ter}+\alpha_{thr,tra}$$

Given that $\alpha_{agg,ter}\leq\alpha_{thr,ter}$ and $\alpha_{agg,tra}\leq\alpha_{thr,tra}$

A minimal separation distance d^{*}_{tra} for intra-floor level and d^{*}_{ter} for inter-floor-level can be expressed as follows [2]

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

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

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

Modeling In-building Small Cells: Mathematical Analysis

Let S_{tra} and S_{ter} denote, respectively, the number of SBSs in clusters of intra-floor and inter-floor levels corresponding to the minimal 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 [2],
$S_{\text{3D}} = S_{\text{tra}} \times S_{\text{ter}}$

- Figure 12 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; edges in blue color represent that the constraint is satisfied for a minimum distance; and 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 floors inter-floor level such that a 3D cluster consists of 18 SBSs.

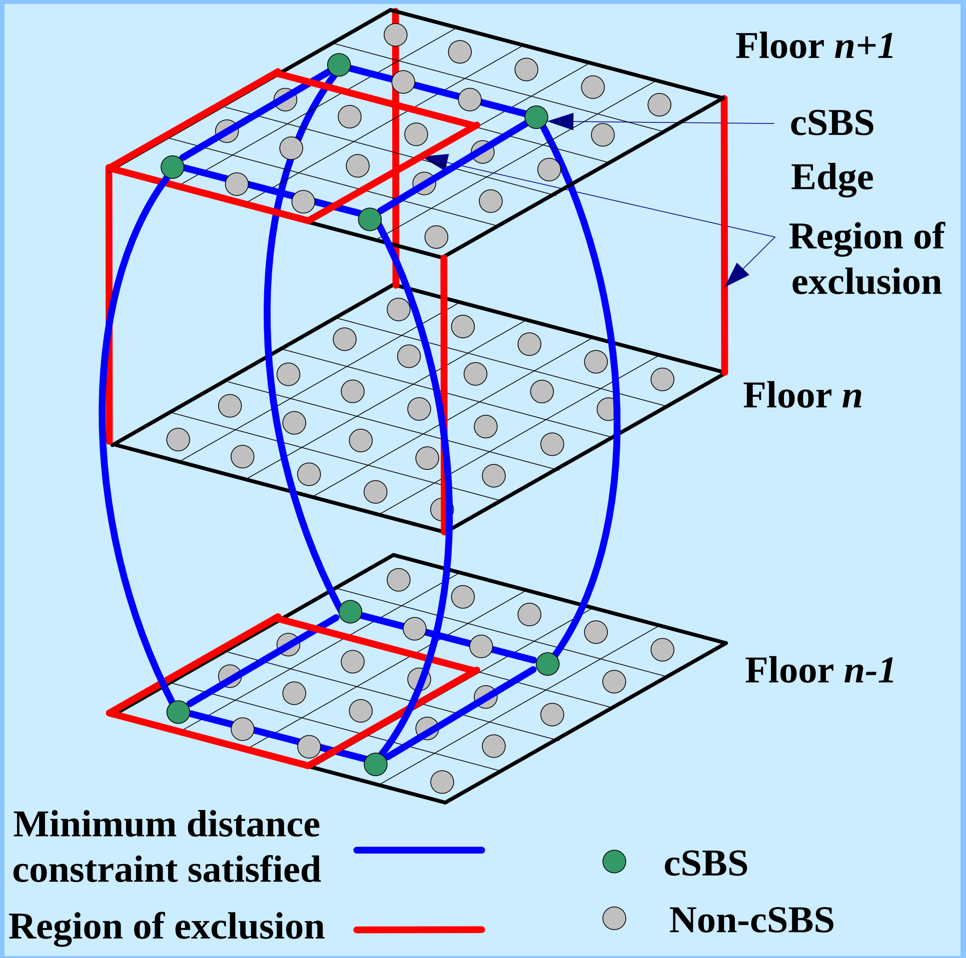


Figure 12. Formation of in-building 3D cluster of SBSs subject to satisfying the minimum distance constraints in both intra-and inter-floor levels to reuse the same spectrum in 3D in-building scenario [2].

Modeling In-building Small Cells: Mathematical Analysis

The minimum distance distances d^*_{tra} and d^*_{ter} are frequency-dependent since distant-dependent path loss in indoor environments is frequency-dependent, and hence vary with the change in carrier frequencies. This correspondingly varies 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 [1].

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

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

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.

Modeling In-building Small cells: Performance Result and Analysis

Assume that $\alpha_f\left(d_{ter}\right) = 55$ dB, $y_{\max,tra} = 8$, and $y_{\max,ter} = 2$ 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 $S_{3D} = S_{tra} \times S_{ter} = 9 \times 1 = 9$

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 times the same mmWave spectrum can be reused to small cells per building is given by, $\frac{180}{9} = 20$.

Since the mmWave path loss within 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 be applicable to both 28 GHz, as well as 60 GHz spectrum bands [1].

Performance Result and Analysis: Impact of 3D Spatial Reuse

Figure 13 shows SE and EE responses when applying 3D spatial reuse of mmWave spectrums to in-building small cells.

From Figure 13(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 Figure 13(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 compared to when no 3D spatial reuse of spectra is exploited.

Hence, exploiting 3D spatial reuse of mmWave spectra within multistory buildings of small cells is a very effective technique to address the expected SE and EE requirements for beyond 5G mobile networks

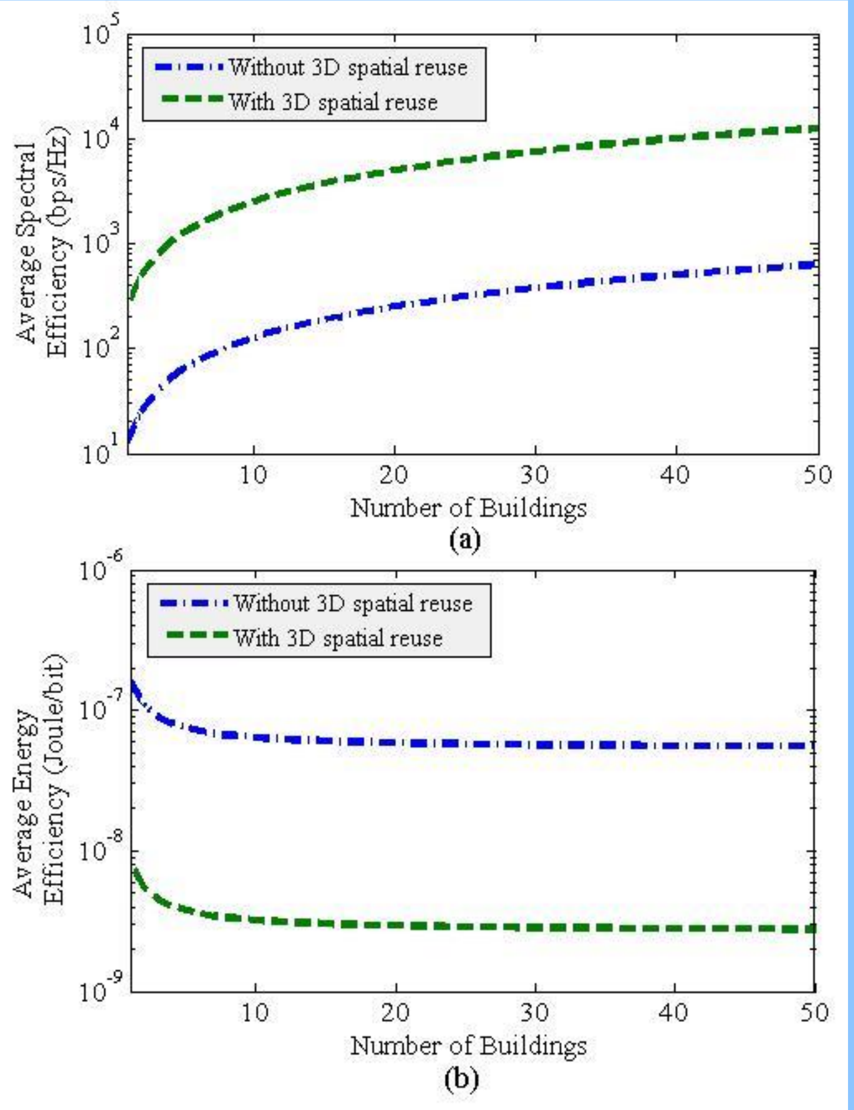


Figure 13. Impact of applying 3D spatial reuse of mmWave spectra to in-building small cells: (a) system-level average SE; (b) system-level average EE [1].

Performance Result and Analysis: Impact of Variation in 3D Spatial Reuse Factor

From Figure 14(a), it can be found that SE improves linearly with an increase in hRF for any value of vRF. Similarly, from 15(a), SE improves linearly with an increase in vRF for any value of hRF. This implies that SE improves by factor defined as the product of vRF and hRF, i.e. (vRF×hRF).

However, from Figures 14(b) and 15(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 is achieved even though vRF increases when hRF gets large enough, i.e. 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 [1]

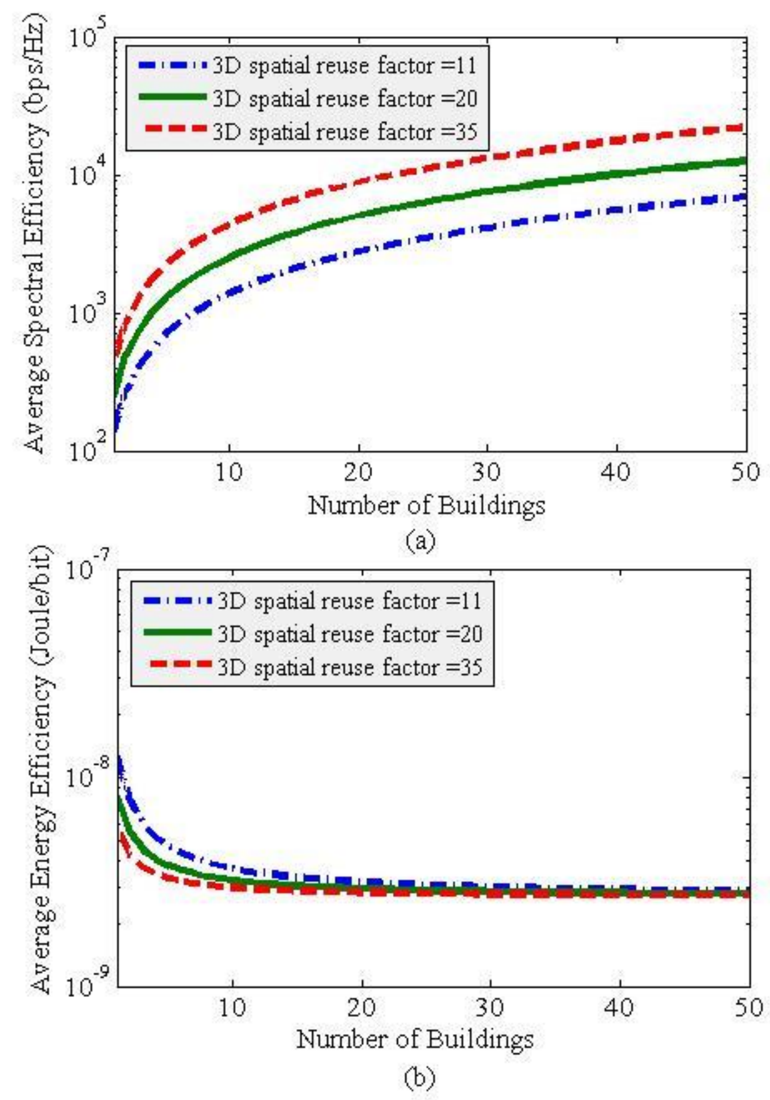


Figure 14. (a) Average SE and (b) Average EE responses for numerous 3D spatial reuse factor per building with variation in hRF, i.e. *L* [1].

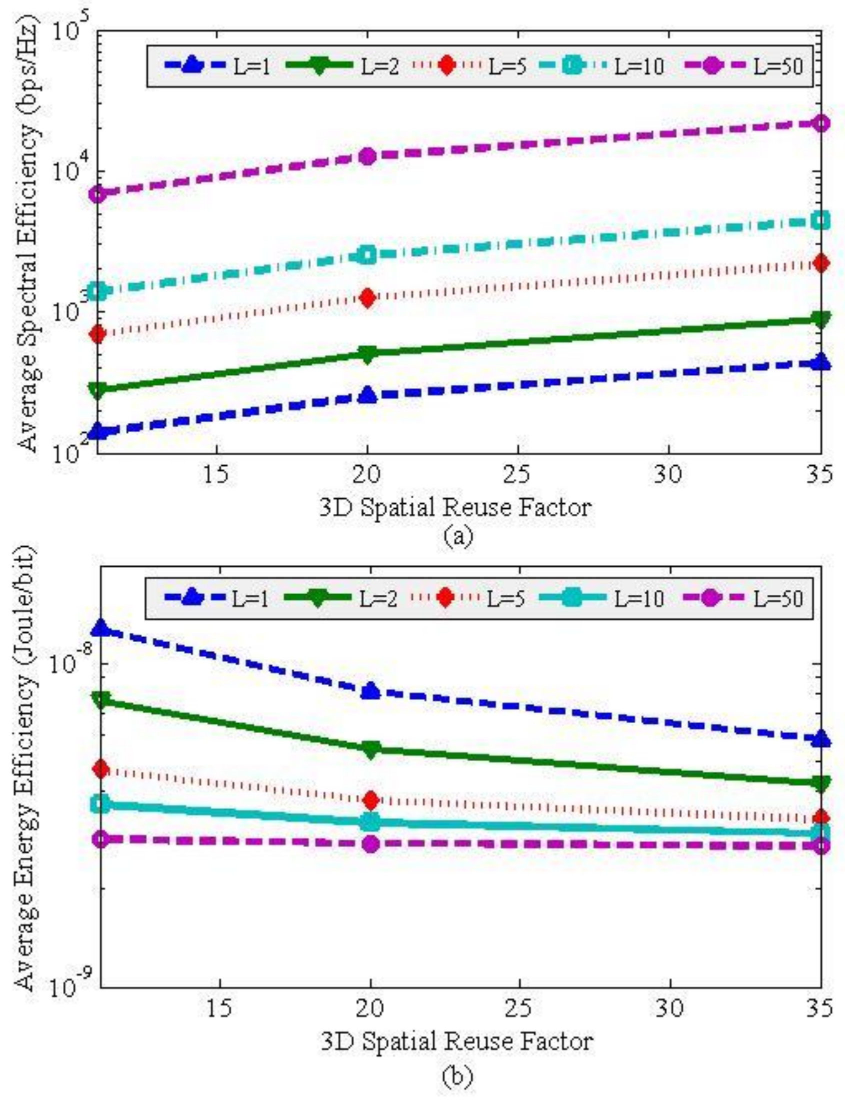


Figure 15. (a) Average SE and (b) Average EE responses for different values of hRF (*L*)wit the variation in 3D spatial reuse factor per building [1].

Cognitive Radio: Background

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 [13], 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.

Cognitive Radio: Background

To address this spectrum under-utilization issue, in recent times, Cognitive radio (CR) has appeared as an enabling technology. In CR, spectrum access is a major function, 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 to serve high data rates and capacity.

Depending on how the collisions between primary user equipments and secondary UEs are prevented while accessing any spectrum, there are three major categories of spectrum access techniques in CR systems as follows.

1. Interweave,
2. Underlay, and
3. Overlay.

In the following, we limit our focus on studying interweave and underlay spectrum access techniques.

Cognitive Radio: Interweave Spectrum Access

In interweave access, SUs can opportunistically access only the spectrum not used by Primary UEs (PUs). The fundamental idea behind the interweave model is to exploit the available under-utilized spectrum to reuse it in an opportunistic manner [14-15] without paying any cost [13]. 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 PUs, for example, when PUs are inactive [13].

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) [16].

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.

Cognitive Radio: Interweave Spectrum Access Technique

In [4], 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 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.

Cognitive Radio: Interweave Spectrum Access

Assume that each MNO *o* has a small cell in each apartment and each small cell can serve the maximum of one UE at a time. Hence, the maximum four different UEs each from one of the four MNOs would exist simultaneously in an apartment. Each UE has two states for existence (i.e., a UE of an MNO *o* may either exist or not) in an apartment.

Let the binary digits 1 and 0 denote respectively the existence and nonexistence of a UE of an MNO *o* in an apartment such that four UEs can coexist in an apartment in a maximum of 2^4 possible ways (Figure 16).

Assume that the existence of four UEs in an apartment for each possible way as shown in Table I is equally likely. Hence, given the existence (i.e., the binary state 1) of a UE of an MNO *o*, UEs of other MNOs can coexist with the UE of MNO *o* in a maximum of eight possible ways as shown in Table I each occurs with a probability of $1/8$ in an apartment of a building.

Note that in the traditional Static Licensed Spectrum Allocation (SLSA) technique, each MNO is licensed exclusively an equal amount of 28 GHz mmWave spectrum.

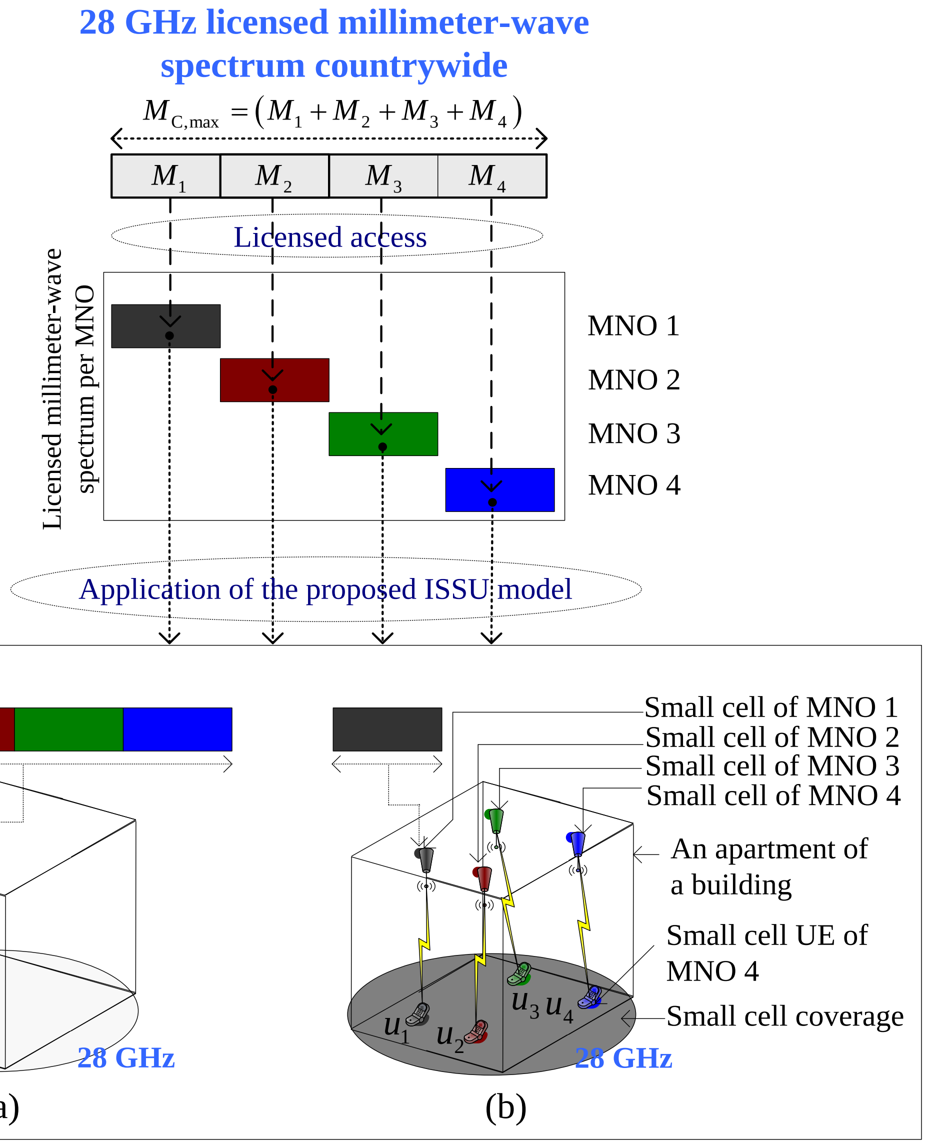


Figure 16. The system architecture of MNO 1 for sharing 28 GHz mmWave spectrum of four MNOs countrywide. (a) a small cell UE of only MNO 1 exists in an apartment and (b) small cell UEs of all MNOs exist in an apartment of a building [4].

Cognitive Radio: Interweave Spectrum Access

TABLE III. CO-EXISTENCE AND SHARED SPECTRUM FOR THE UE u_1[4]

u_1	u_2	u_3	u_4	Spectrum for u_1	
				Shared	Total
1	0	0	0	3M	4M
1	0	0	1	2M	3M
1	0	1	0	2M	3M
1	0	1	1	M	2M
1	1	0	0	2M	3M
1	1	0	1	M	2M
1	1	1	0	M	2M
1	1	1	1	0	M

Using [4] and from Figure 17, it can be found that due to applying ISSU, the average capacity, as well as the SE, performances of an MNO *o* (i.e. an s-MNO) are improved by about 150%, whereas the EE performance is improved by about 60%.

Using Table III, 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 of 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 Figure 17.

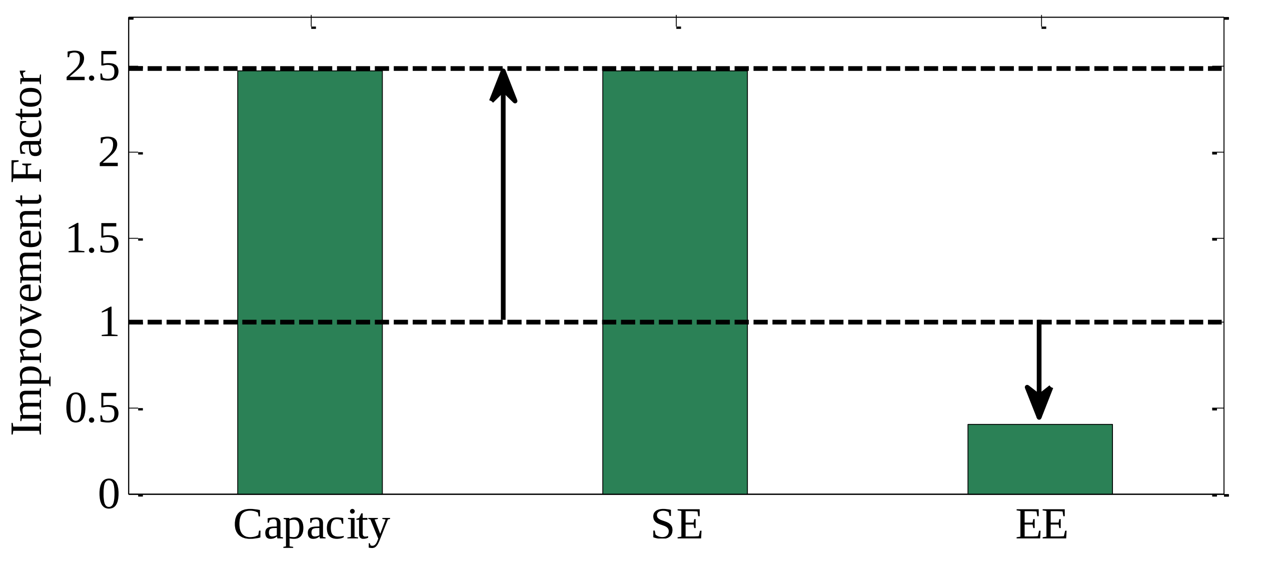


Figure 17. Average capacity, SE, and EE performance improvement factors for an s-MNO with applying ISSU for a single building of small cells [4]

Cognitive Radio: Underlay Spectrum Access

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.

The underlay spectrum access technique takes advantage of several aspects. For example,

- The complex spectrum sensing mechanism in CR systems is not needed [17] 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.

Cognitive Radio: Underlay Spectrum Access

In [5], 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.

- 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.

Cognitive Radio: Underlay Spectrum Access

$P_{\mathrm{SC,red},o}$ denotes the reduced transmission power of an SBS of MNO o

$I_{\mathrm{thr,und}}$ denotes the predefined value of the maximum CCI that can be caused by an SBS to a UE of a p-MNO

κ denotes the interference channel gain

The transmission power of an SBS of MNO o when operating at the shared spectra of other MNOs $\boldsymbol{O}\backslash o$ using the proposed technique can be adapted with $I_{\mathrm{thr,und}}$ as follows.

$$P_{\mathrm{SC,und},o} = \begin{cases} P_{\mathrm{SC,red},o}, & \left(\kappa \times P_{\mathrm{SC,red},o}\right) \le I_{\mathrm{thr,und}} \\ \left(I_{\mathrm{thr,und}}/\kappa\right), & \left(\kappa \times P_{\mathrm{SC,red},o}\right) > I_{\mathrm{thr,und}} \end{cases}$$

- The transmission power of an SBS is upper limited by 20% of its maximum power when operating at the shared spectra of p-MNOs (Figure 18).
- Also, for each SBS, a separate transceiver is assumed to operate at the shared spectra of all p-MNOs.

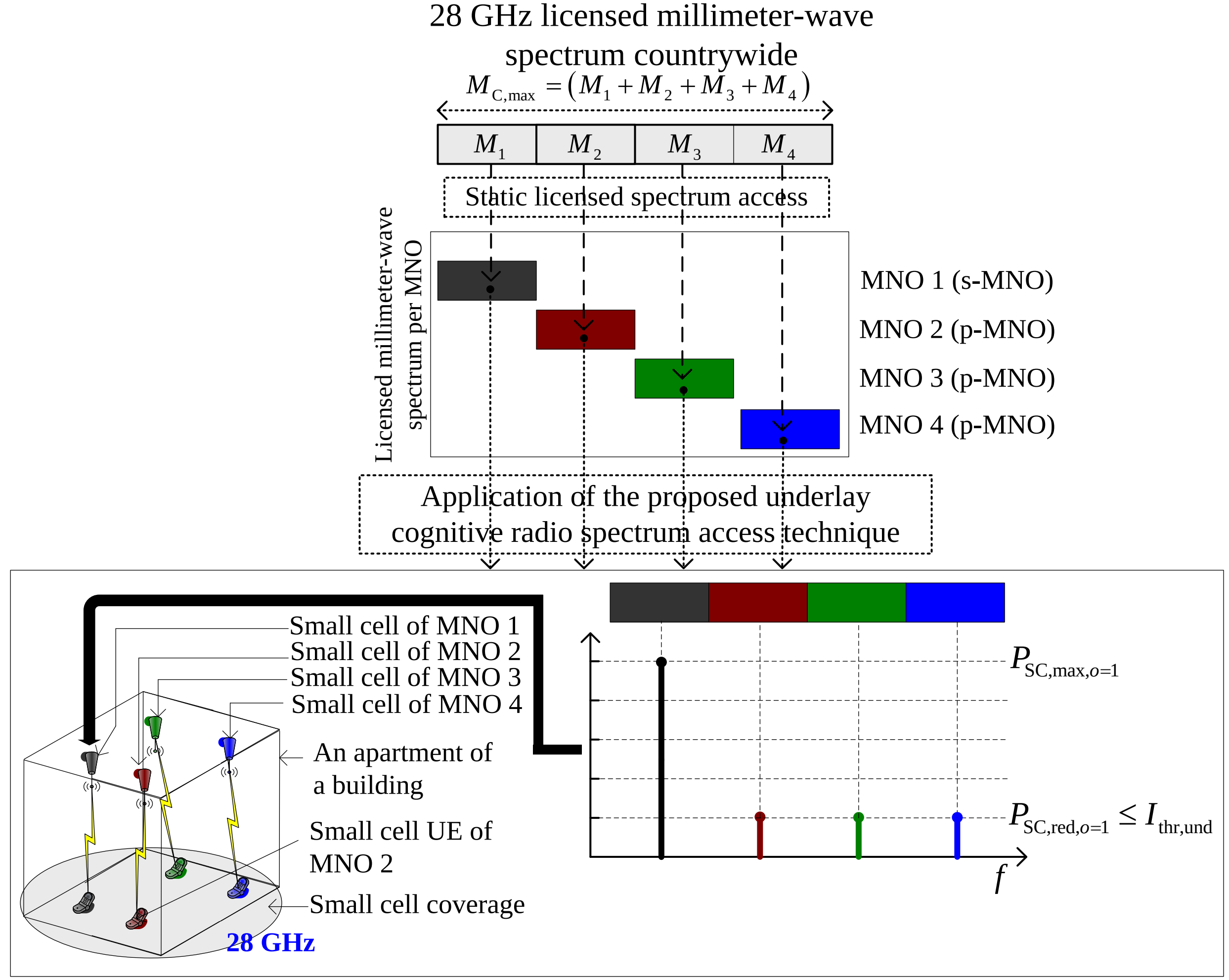


Figure 18. A system architecture with four MNOs in a country. $P_{\mathrm{SC,max},o=1}$, $P_{\mathrm{SC,red},o=1}$ and $I_{\mathrm{thr,und}}$ denote respectively the maximum transmission power, reduced transmission power, and predefined interference threshold of a small cell of MNO 1.

Cognitive Radio: Underlay Spectrum Access

Using [5], Figure 19 shows improvement factors in terms of average capacity, SE, and EE performances for MNO 1 due to applying the proposed technique over the traditional SLSA technique for a single building of small cells.

It can be found that the proposed technique improves average capacity, SE, and EE of MNO 1 substantially as compared to that of the traditional SLSA technique.

This can be clarified by the fact that the proposed technique allows small cells of MNO 1 to operate at the additional shared spectra of three other p-MNOs, which results in increasing its available spectrum by three times.

Since the capacity and hence the SE is directly proportional, whereas the EE is inversely proportional, to the available spectrum, the proposed technique improves SE by about 2.67 times, whereas EE by about 72.74%, of MNO 1 by operating each small cell at reduced power, as shown in Figure 19 [5].

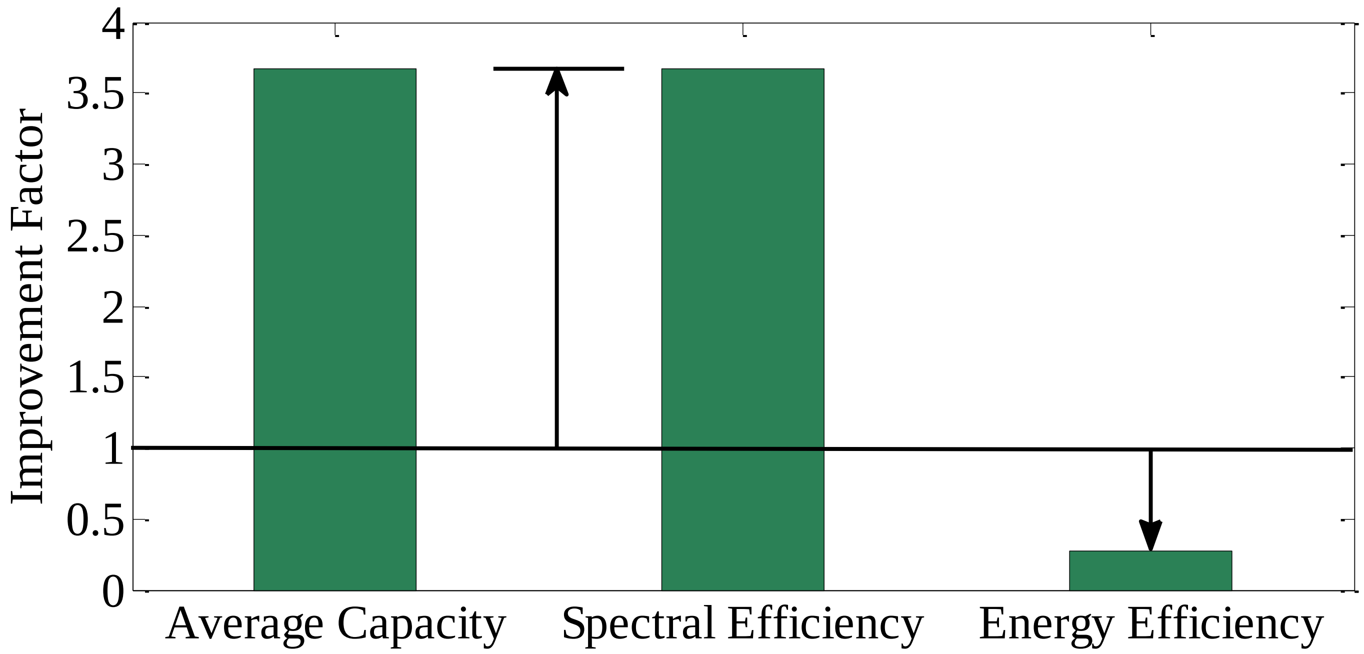


Figure 19. Average capacity, SE, and EE improvement for MNO 1 of the proposed UCRSA technique over the traditional SLSA technique for *a single building of small cells* [5].

Cognitive Radio: Hybrid Interweave-Underlay Spectrum Access

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 the interweave access when the spectrum of PUs is idle and the 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.

Cognitive Radio: Hybrid Interweave-Underlay Spectrum Access

In [6], 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 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.

- 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.

Cognitive Radio: Hybrid Interweave-Underlay Spectrum Access

Like underlay spectrum access, assume that each MNO o has an SBS in each apartment, and each SBS can serve the maximum of one UE at a time (Figure 20). Assume that there are 4 MNOs in a country such that $o \in \boldsymbol{O} = \{1,2,3,4\}$.

So, a maximum of four different UEs each from one MNO may exist at once in an apartment. Each UE has two states for existence (i.e., a UE of an MNO may either exist or not) in an apartment. Let the binary digits 1 and 0 denote, respectively, the existence and nonexistence of a UE of an MNO o in an apartment such that four UEs can coexist in an apartment in a maximum of 2^4 possible ways.

Assume that the existence of four UEs in an apartment for each possible way is equally likely. Hence, given the existence (i.e., the binary state 1) of a UE of an MNO o (i.e., an s-MNO), UEs of other MNOs $\boldsymbol{O} \backslash o$ (i.e., p-MNOs) can coexist with the UE of MNO o in a maximum of eight possible ways, as shown in Table I, each occurs with a probability of $1/8$ in an apartment.

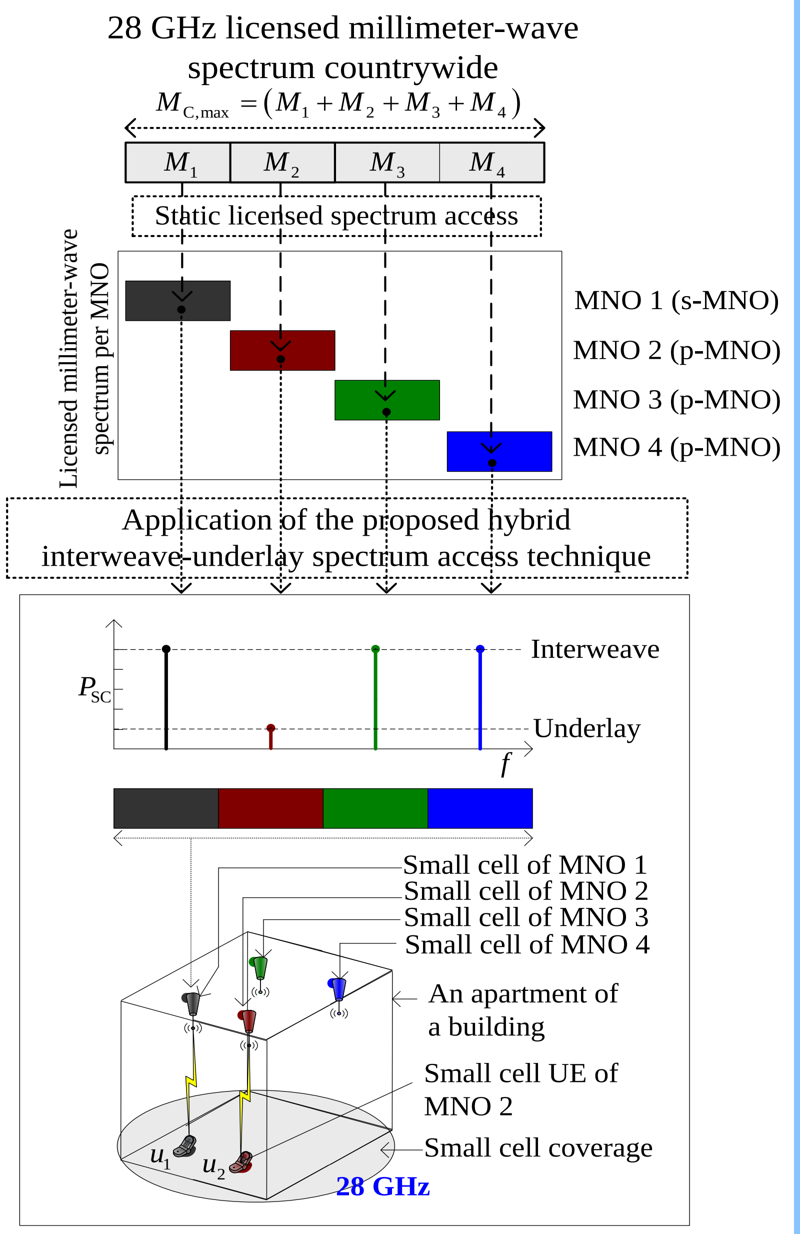


Figure 20. A system architecture with four MNOs in a country.

P_{SC} denotes the transmission power of an in-building small cell base station of MNO 1.

Cognitive Radio: Hybrid Interweave-Underlay Spectrum Access

TABLE IV: CO-EXISTENCE AND SHARED SPECTRUM FOR UE u_1 OF MNO 1 USING THE PROPOSED TECHNIQUE.

u_1	u_2	u_3	u_4	**Shared spectrum for u_1**		**Licensed spectrum for u_1**
				Interweave	**Underlay**	**Both interweave and underlay**
1	**0**	**0**	**0**	**3M**	**0**	**M**
1	**0**	**0**	**1**	**2M**	**M**	**M**
1	**0**	**1**	**0**	**2M**	**M**	**M**
1	**0**	**1**	**1**	**M**	**2M**	**M**
1	**1**	**0**	**0**	**2M**	**M**	**M**
1	**1**	**0**	**1**	**M**	**2M**	**M**
1	**1**	**1**	**0**	**M**	**2M**	**M**
1	**1**	**1**	**1**	**0**	**3M**	**M**

For the underlay access, we assume that the transmission power of an SBS is upper limited by 20% of its maximum power. To allow flexibility in switching between the interweave and underlay accesses, for each SBS, a separate transceiver is assumed to operate at the shared spectrum of each p-MNO.

Using [6], Figure 21 shows that the hybrid technique improves both the SE and EE metrics of MNO 1 considerably as compared to that of the traditional interweave and underlay techniques when applied separately.

This is because, using Table IV, the maximum amount of the shared spectrum obtained by employing the hybrid technique is 3 times (interweave and underlay techniques each contributing 1.5 times) the spectrum of MNO 1 of *M* RBs.

Since the capacity, and hence SE, is directly proportional, whereas the EE is inversely proportional, to the spectrum, the hybrid technique improves SE by about 2.82 times, whereas EE by about 73%, of MNO 1.

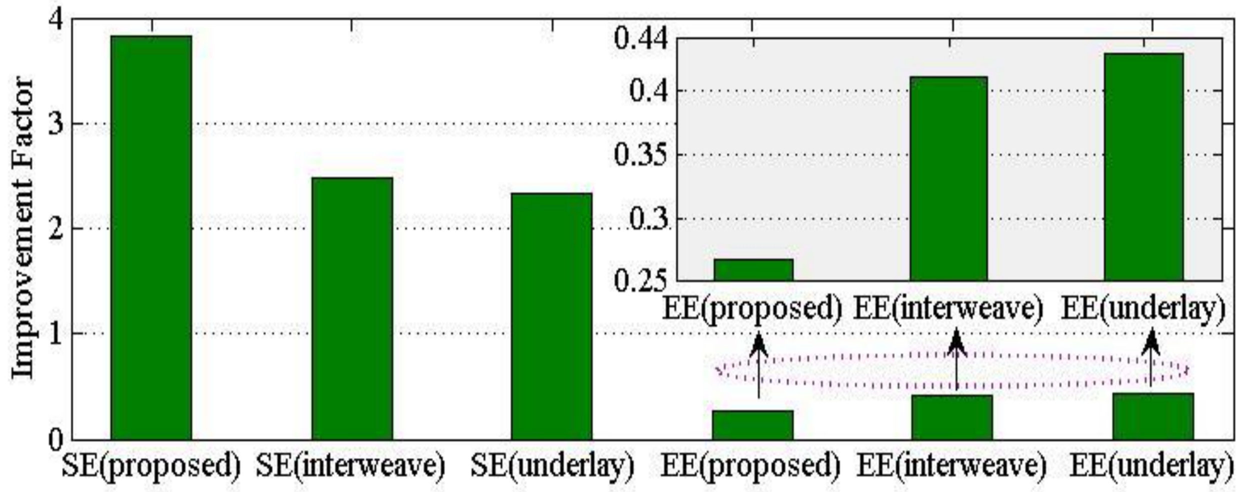


Figure 21. SE and EE improvement factors for an s-MNO (i.e., MNO 1) due to applying different techniques for a single building of SBSs.

Conclusion

In this tutorial, we have presented how to exploit the potential of small cells to address high capacity demands of in-building users in cellular mobile networks. In this regard, we have explored three major directions, including spectrum accessibility, spectral efficiency improvement, and network densification, to improve network capacity indoors. It has been shown that the 3-Dimensional (3D) spatial reuse of millimetre-wave spectra by capturing 3D effects on indoor signal propagations with in-building multiband-enabled ultra-dense small cells to avail additional spectrum using Dynamic Spectrum Sharing (DSS), along with exploiting Cognitive Radio (CR) technology to improve spectrum utilization, can address enormous capacity demand of mobile networks.

In doing so, we have first given a short introduction to in-building small sells, including fundamental feature, access mechanism, and suitable spectrum bands. Following so, in-building signal propagation characteristics, including path loss and wall and floor penetration losses of a building, have been discussed.

Based on the Shannon's capacity formula, we have then shown the application of enabling technologies (e.g., DSS, CR, and frequency reuse strategy) along major three directions, namely spectrum accessibility, spectral efficiency improvement, and network densification, toward achieving high network capacity with relevant performance results and illustrations.

The contents in the presentation, in terms of texts, figures, tables, equations, and other forms, have been taken mainly from the presenter's research works [1-6] mentioned in the reference section, and hence can be found merged partly or fully with those works [1-6]. The tutorial has been prepared with the purpose of disseminating existing information in research works [1-6] to address the high capacity indoors issue. The presenter expects that the tutorial should help learn about how to exploit small cells using the state-of-the-art techniques and technologies recommended, as well as in operation, to achieve ever growing in-building high capacity demands, particularly in dense urban environments.

Appendix I

TABLE V. A LIST OF ABBREVIATIONS

Abbreviation	Definition
2D	2-Dimensional
3D	3-Dimensional
4G	Fourth-Generation
5G	Fifth-Generation
6G	Sixth-Generation
ABS	Almost Blank Subframe
APP	ABS Pattern Period
BS	Base Station
CCI	Co-Channel Interference
CMOS	Complementary Metal-Oxide-Semiconductor
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
LOS	Line-Of-Sight
LSA	Licensed Shared Access
MBS	Macrocell Base Station
mmWave	Millimeter-Wave

Abbreviation	Definition
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

Acknowledgement

- This tutorial is mainly based on the presenter's research works [1-6] mentioned in the reference section. Consequently, contents in the presentation slides, as well as in this document, in terms of texts, figures, tables, equations, and other forms, can be found merged partly or fully with those works [1-6].
- This tutorial presentation in any form should not be considered a new or novel one. It is prepared with the purpose of disseminating existing information (toward addressing a specific issue highlighted by the title of the tutorial) in the form of research works [1-6] provided by the presenter as mentioned in the reference.
- For interested readers, please refer to the relevant works [1-6] for any sort of further information. References other than these [1-6] are cited in the appropriate places, wherever used.

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End of the Presentation

Thank You …