# Hybrid Interweave-Underlay Millimeter-Wave Spectrum Access in Multi-Operator Cognitive Radio Networks Toward 6G

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# 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 50 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
- 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

- Problem statement
- Scope
  - System Architecture and Proposed Technique
  - Mathematical Analysis
    - Performance Results and Analysis
    - Conclusion
      - References

# Problem Statement

- Radio **spectrum scarcity** has become a major issue in mobile communications due to **static allocation (SA)** of spectrum to MNOs.
- SA causes a great portion of the spectrum to be left **unused** in time, frequency, and space, resulting in **poor spectrum utilization**.

- Recently, **Cognitive Radio** (CR) has been considered as a key enabling technology to address this spectrum scarcity issue.
- In CR, **spectrum access** is a major function, which **prevents collisions** between primary UEs (PUs) and Secondary UEs (SUs) in accessing any spectrum.
- In this regard, **interweave** and **underlay** are two major spectrum access categories in CR.

# Problem Statement – cont'd

**Interweave access**: SUs can opportunistically access only the spectrum **not used by PUs**

**Pros:** SUs are allowed to transmit at the maximum power.

**Cons**: needs additional spectrum sensing by SUs to find an idle spectrum of PUs.

**Underlay access**: SUs can **simultaneously access the spectrum of PUs** subject to satisfying interference threshold set by PUs.

**Pros**: no spectrum sensing is needed by SUs.

**Cons**: suffers from the reduced transmission power of SUs to limit CCI to PUs.

Hence, though both Interweave and underlay access have **pros and cons**, the combination of these two can **maximize the SE and EE**.

**i.e.,** SUs can explore interweave (max power) **when the spectrum of PUs is idle,** whereas **underlay when the spectrum of PUs is busy** (reduced power).

# Problem Statement – cont’d

Also, **most data are originated** indoors, particularly in dense urban areas with a large number of multistory buildings.

Due to the **favorable propagation characteristics** such as

- low interference effects and
- existence of Line-of-Sight (LOS) components,
- large bandwidth

**operating small cells at the mmWave spectrum in such buildings** can be a promising candidate to provide high data rates and capacity.

In line with so, a **hybrid interweave-underlay spectrum access technique** for sharing the licensed mmWave spectrum of one MNO with in-building small cells of another to **increase its available spectrum within multistory buildings** can play a vital role in serving high capacity and data rates indoors.

# Scope

- The **proposed technique** along with the **system architecture** is presented.
- Relevant **mathematical analysis** are performed to derive average capacity, SE, and EE performance metrics for s-MNOs.
- Extensive numerical and simulation results and analyses for an s-MNO are carried out.

It is **demonstrated** that the **proposed technique can satisfy** both the **SE and EE** requirements for **6G** mobile systems.

# System Architecture and Proposed Technique

## (a) System Architecture

- Four MNOs (i.e., MNO 1, MNO 2, MNO 3, and MNO 4) are operating in a country.
- Each MNO has a similar system architecture consisting of three types of Base Stations (BSs), namely Macrocell BSs (MBSs), Picocell BSs (PBSs), and Small Cell BSs (SBSs).

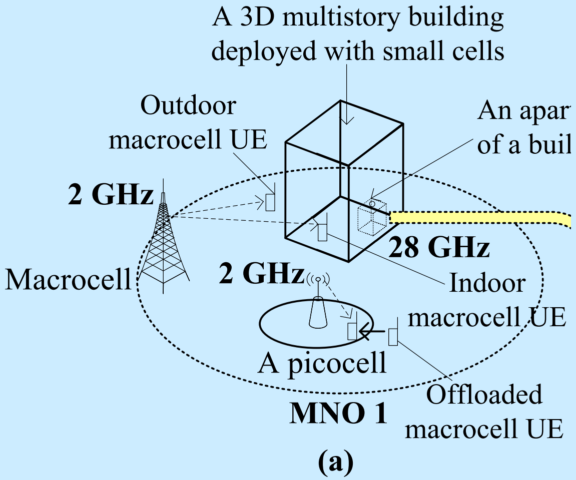


Figure 1. A system architecture consisting of four MNOs in a country.

- For simplicity, we show the detailed architecture of only one MNO (i.e., MNO 1) in Figure 1(a). All SBSs are deployed only within 3-Dimensional (3D) multistory buildings each serving one UE at a time.
- SBSs within each building are considered operating at the 28 GHz mmWave spectrum, whereas MBSs and PBSs are operating at the 2 GHz spectrum (Figure 1(a)).

# System Architecture and Proposed Technique

## (b) Proposed Technique

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,** whereas at a **reduced transmission power if a UE of the p-MNO is present**. The reduced transmission power is varied with the **predefined interference** threshold set by the p-MNO.

- Each MNO is given a license for an **equal amount** of 28 GHz mmWave spectrum.
- Spectrum of one MNO can be shared with in-building SBSs of another.
- Figures 1(b)-1(d) show an example for sharing the spectra of MNO 2, MNO 3, and MNO 4 as p-MNOs with an in-building SBS of MNO 1 as an s-MNO using the proposed technique.
- Note: Maximum of **two UEs** (one from MNO 1 and the other from an p-MNO) can exist simultaneously in the coverage of an SBS.

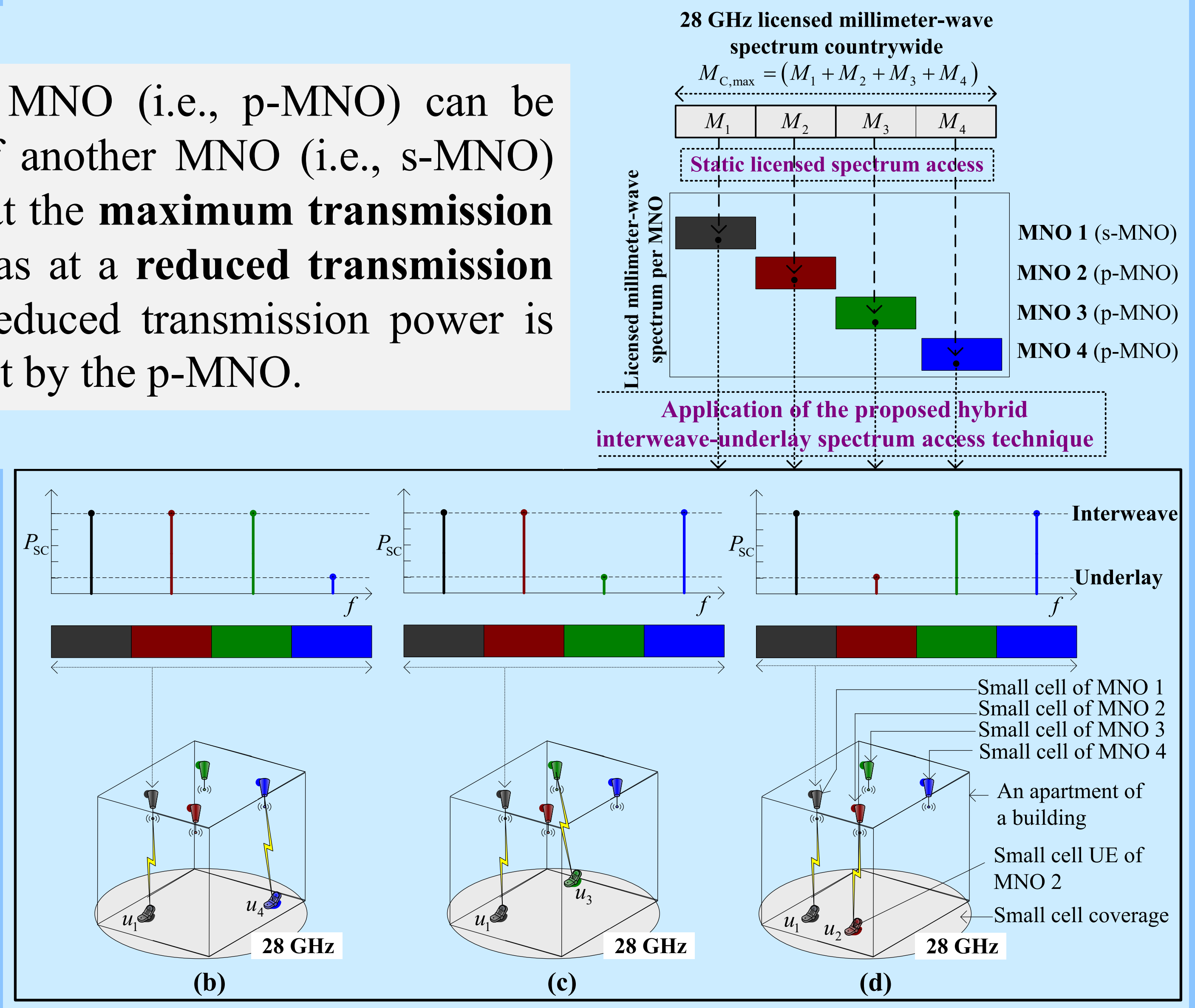


Figure 1. A system architecture consisting of four MNOs in a country.

# Mathematical Analysis

$$\sigma_{t,i,o}\left(\rho_{t,i,o}\right)=\begin{cases}0, & \rho_{t,i,o}<-10\,\mathrm{dB}\\ \beta\log_2\left(1+10^{\left(\rho_{t,i,o}(\mathrm{dB})/10\right)}\right), & -10\,\mathrm{dB}\le\rho_{t,i,o}\le 22\,\mathrm{dB}\\ 4.4, & \rho_{t,i,o}>22\,\mathrm{dB}\end{cases}$$

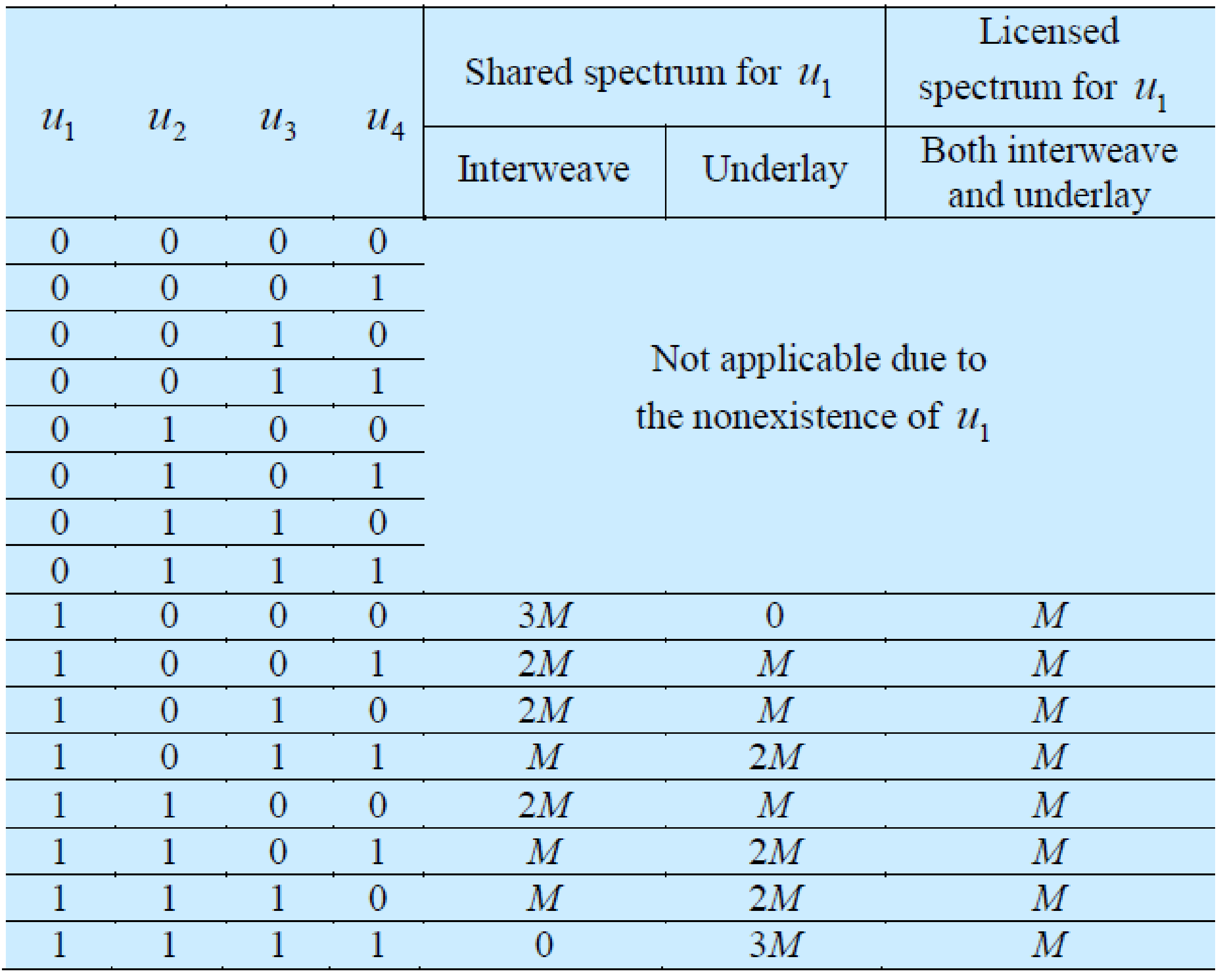
$$\sigma_{\mathrm{MBS},o}=\sum_{t=1}^{Q}\sum_{i=1}^{M_{\mathrm{MBS},o}}\sigma_{t,i,o}\left(\rho_{t,i,o}\right)$$

For 4 MNOs in a country such that $o\in\boldsymbol{O}=\{1,2,3,4\}$

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 (Table I)

Assume that the existence of four UEs in an apartment for each possible way as shown in Table I is **equally likely**.

Table I. 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 |
| 0 | 0 | 0 | 0 | Not applicable due to the nonexistence of $u_1$ | | |
| 0 | 0 | 0 | 1 | | | |
| 0 | 0 | 1 | 0 | | | |
| 0 | 0 | 1 | 1 | | | |
| 0 | 1 | 0 | 0 | | | |
| 0 | 1 | 0 | 1 | | | |
| 0 | 1 | 1 | 0 | | | |
| 0 | 1 | 1 | 1 | | | |
| 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 | $3M$ | $M$ |

# Mathematical Analysis

Capacity served by an SBS of an MNO $o$ using the interweave access at the shared spectrum of MNOs $\boldsymbol{O}\backslash o$

$$\sigma_{s,o,\text{int}}=\left(\begin{array}{l}\left(3\sum_{t=1}^{(Q/8)}\sum_{i=1}^{M}\sigma_{t,i,o,\text{int}}\left(\rho_{t,i,o,\text{int}}\right)\right)\\+\left(3\sum_{t=1}^{(Q/8)}\sum_{i=1}^{2M}\sigma_{t,i,o,\text{int}}\left(\rho_{t,i,o,\text{int}}\right)\right)\\+\sum_{t=1}^{(Q/8)}\sum_{i=1}^{3M}\sigma_{t,i,o,\text{int}}\left(\rho_{t,i,o,\text{int}}\right)\end{array}\right)$$

Capacity served by an SBS of an MNO $o$ using the underlay access at the shared spectrum

$$\sigma_{s,o,\text{und}}=\left(\begin{array}{l}\left(3\sum_{t=1}^{(Q/8)}\sum_{i=1}^{M}\sigma_{t,i,o,\text{und}}\left(\rho_{t,i,o,\text{und}}\right)\right)\\+\left(3\sum_{t=1}^{(Q/8)}\sum_{i=1}^{2M}\sigma_{t,i,o,\text{und}}\left(\rho_{t,i,o,\text{und}}\right)\right)\\+\sum_{t=1}^{(Q/8)}\sum_{i=1}^{3M}\sigma_{t,i,o,\text{und}}\left(\rho_{t,i,o,\text{und}}\right)\end{array}\right)$$

Capacity served by an SBS of an MNO $o$ at the licensed spectrum of $M$ of MNO $o$ itself

$$\sigma_{s,o,\text{lic}}=\sum_{t=1}^{Q}\sum_{i=1}^{M}\sigma_{t,i,o,\text{lic}}\left(\rho_{t,i,o,\text{lic}}\right)$$

Overall aggregate capacity, SE, and EE served by an SBS of an MNO $o$ using the proposed technique

$$\sigma_{s,o,\text{prop}}=\left(\sigma_{s,o,\text{lic}}+\sigma_{s,o,\text{int}}+\sigma_{s,o,\text{und}}\right)$$

$$\sigma_{S_{\text{F}},o,\text{prop}}=\sum_{s=1}^{S_{\text{F}}}\sigma_{s,o,\text{prop}}$$

$$\sigma_{\text{cap},o,\text{prop}}^{\text{sys}}\left(L\right)=\sigma_{\text{MBS},o}+\left(L\,\sigma_{S_{\text{F}},o,\text{prop}}\right)$$

$$\sigma_{\text{SE},o,\text{prop}}^{\text{sys}}\left(L\right)=\sigma_{\text{cap},o,\text{prop}}^{\text{sys}}\left(L\right)\Big/\left(\left(M_{\text{MBS},o}+M\right)Q\right)$$

$$\sigma_{\text{EE},o,\text{prop}}^{\text{sys}}\left(L\right)=\left(\begin{array}{l}\left(\begin{array}{l}\left(L\,S_{\text{F}}\right)\\\left(\begin{array}{l}P_{\text{SC,lic},o}+\\\left(1.5\left(P_{\text{SC,int},o}+P_{\text{SC,und},o}\right)\right)\end{array}\right)\end{array}\right)\\+\left(S_{\text{P}}P_{\text{PC}}\right)+\left(S_{\text{M}}P_{\text{MC}}\right)\end{array}\right)\Bigg/\left(\sigma_{\text{cap},o,\text{prop}}^{\text{sys}}\left(L\right)/Q\right)$$

# Mathematical Analysis

## Traditional Static Licensed Spectrum Allocation (SLSA) technique

Each MNO is licensed exclusively for an equal amount of 28 GHz mmWave spectrum of $M$ RBs.

$$\sigma^{\mathrm{sys}}_{\mathrm{cap},o,\mathrm{SLSA}}\left(L\right)=\sigma_{\mathrm{MBS},o}+\left(L\,\sigma_{S_{\mathrm{F}},o,\mathrm{SLSA}}\right)$$

$$\sigma_{S_{\mathrm{F}},o,\mathrm{SLSA}}=\sum_{s=1}^{S_{\mathrm{F}}}\sum_{t\in\boldsymbol{T}}\sum_{i=1}^{M}\sigma_{s,t,i,o}\left(\rho_{s,t,i,o}\right)$$

$$\sigma^{\mathrm{sys}}_{\mathrm{SE},o,\mathrm{SLSA}}\left(L\right)=\sigma^{\mathrm{sys}}_{\mathrm{cap},o,\mathrm{SLSA}}\left(L\right)\Big/\left(\left(M_{\mathrm{MBS},o}+M\right)Q\right)$$

$$\sigma^{\mathrm{sys}}_{\mathrm{EE},o}\left(L\right)=\begin{pmatrix}\left(L\,S_{\mathrm{F}}P_{\mathrm{SC}}\right)\\+\left(S_{\mathrm{P}}P_{\mathrm{PC}}\right)+\left(S_{\mathrm{M}}P_{\mathrm{MC}}\right)\end{pmatrix}\Bigg/\left(\sigma^{\mathrm{sys}}_{\mathrm{cap},o,\mathrm{SLSA}}\left(L\right)/Q\right)$$

## Improvement Factors for capacity, SE, and EE:

$$\sigma^{\mathrm{sys}}_{\mathrm{cap},o,\mathrm{IF}}\left(L\right)=\sigma^{\mathrm{sys}}_{\mathrm{cap},o,\mathrm{prop}}\left(L\right)\Big/\sigma^{\mathrm{sys}}_{\mathrm{cap},o,\mathrm{SLSA}}\left(L\right)$$

$$\sigma^{\mathrm{sys}}_{\mathrm{SE},o,\mathrm{IF}}\left(L\right)=\sigma^{\mathrm{sys}}_{\mathrm{SE},o,\mathrm{prop}}\left(L\right)\Big/\sigma^{\mathrm{sys}}_{\mathrm{SE},o,\mathrm{SLSA}}\left(L\right)$$

$$\sigma^{\mathrm{sys}}_{\mathrm{EE},o,\mathrm{IF}}\left(L\right)=\sigma^{\mathrm{sys}}_{\mathrm{EE},o,\mathrm{prop}}\left(L\right)\Big/\sigma^{\mathrm{sys}}_{\mathrm{EE},o,\mathrm{SLSA}}\left(L\right)$$

# Performance Results and Analysis

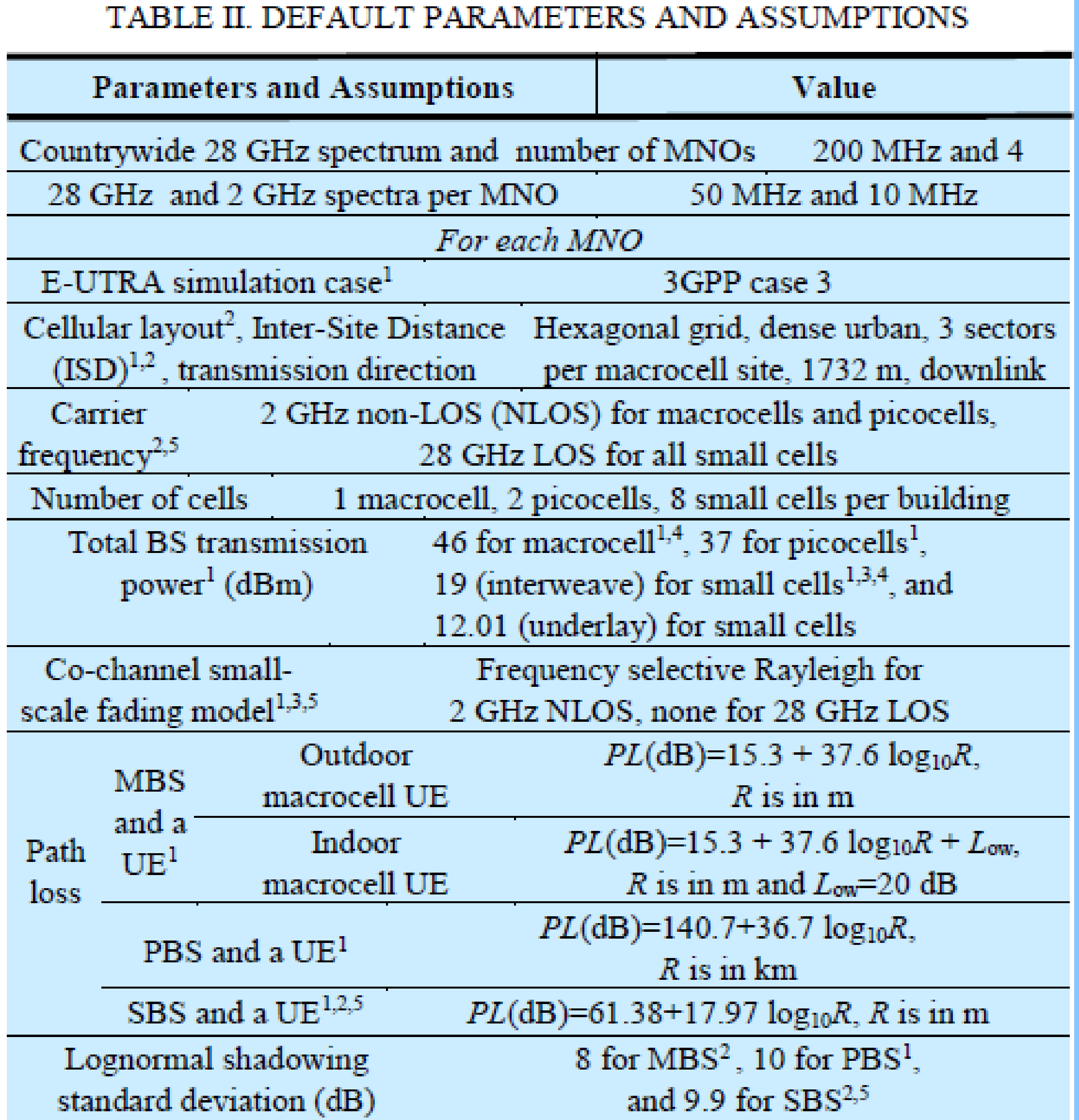
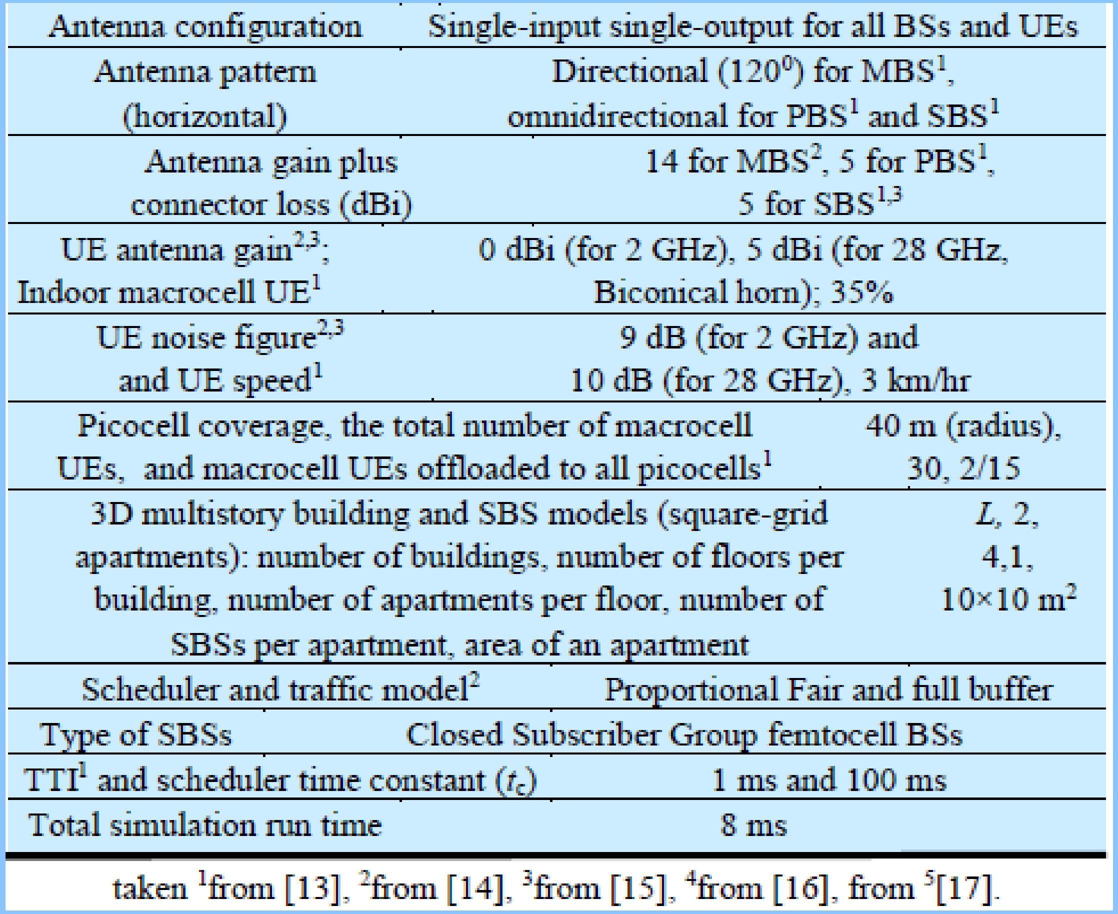


TABLE II. DEFAULT PARAMETERS AND ASSUMPTIONS

| Parameters and Assumptions | Value |
|---|---|
| Countrywide 28 GHz spectrum and number of MNOs | 200 MHz and 4 |
| 28 GHz and 2 GHz spectra per MNO | 50 MHz and 10 MHz |
| *For each MNO* | |
| E-UTRA simulation case[1] | 3GPP case 3 |
| Cellular layout[2], Inter-Site Distance (ISD)[1,2], transmission direction | Hexagonal grid, dense urban, 3 sectors per macrocell site, 1732 m, downlink |
| Carrier frequency[2,5] | 2 GHz non-LOS (NLOS) for macrocells and picocells, 28 GHz LOS for all small cells |
| Number of cells | 1 macrocell, 2 picocells, 8 small cells per building |
| Total BS transmission power[1] (dBm) | 46 for macrocell[1,4], 37 for picocells[1], 19 (interweave) for small cells[1,3,4], and 12.01 (underlay) for small cells |
| Co-channel small-scale fading model[1,3,5] | Frequency selective Rayleigh for 2 GHz NLOS, none for 28 GHz LOS |
| Path loss: MBS and a UE[1], Outdoor macrocell UE | $PL$(dB)=15.3 + 37.6 $\log_{10}R$, $R$ is in m |
| Path loss: MBS and a UE[1], Indoor macrocell UE | $PL$(dB)=15.3 + 37.6 $\log_{10}R + L_{ow}$, $R$ is in m and $L_{ow}$=20 dB |
| Path loss: PBS and a UE[1] | $PL$(dB)=140.7+36.7 $\log_{10}R$, $R$ is in km |
| Path loss: SBS and a UE[1,2,5] | $PL$(dB)=61.38+17.97 $\log_{10}R$, $R$ is in m |
| Lognormal shadowing standard deviation (dB) | 8 for MBS[2], 10 for PBS[1], and 9.9 for SBS[2,5] |



| Parameters and Assumptions | Value |
|---|---|
| Antenna configuration | Single-input single-output for all BSs and UEs |
| Antenna pattern (horizontal) | Directional (120$^0$) for MBS[1], omnidirectional for PBS[1] and SBS[1] |
| Antenna gain plus connector loss (dBi) | 14 for MBS[2], 5 for PBS[1], 5 for SBS[1,3] |
| UE antenna gain[2,3]; Indoor macrocell UE[1] | 0 dBi (for 2 GHz), 5 dBi (for 28 GHz, Biconical horn); 35% |
| UE noise figure[2,3] and UE speed[1] | 9 dB (for 2 GHz) and 10 dB (for 28 GHz), 3 km/hr |
| Picocell coverage, the total number of macrocell UEs, and macrocell UEs offloaded to all picocells[1] | 40 m (radius), 30, 2/15 |
| 3D multistory building and SBS models (square-grid apartments): number of buildings, number of floors per building, number of apartments per floor, number of SBSs per apartment, area of an apartment | $L$, 2, 4,1, 10×10 m$^2$ |
| Scheduler and traffic model[2] | Proportional Fair and full buffer |
| Type of SBSs | Closed Subscriber Group femtocell BSs |
| TTI[1] and scheduler time constant ($t_c$) | 1 ms and 100 ms |
| Total simulation run time | 8 ms |

taken [1]from [13], [2]from [14], [3]from [15], [4]from [16], from [5][17].

- 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 $M$ RBs of each p-MNO.

# Performance Results and Analysis

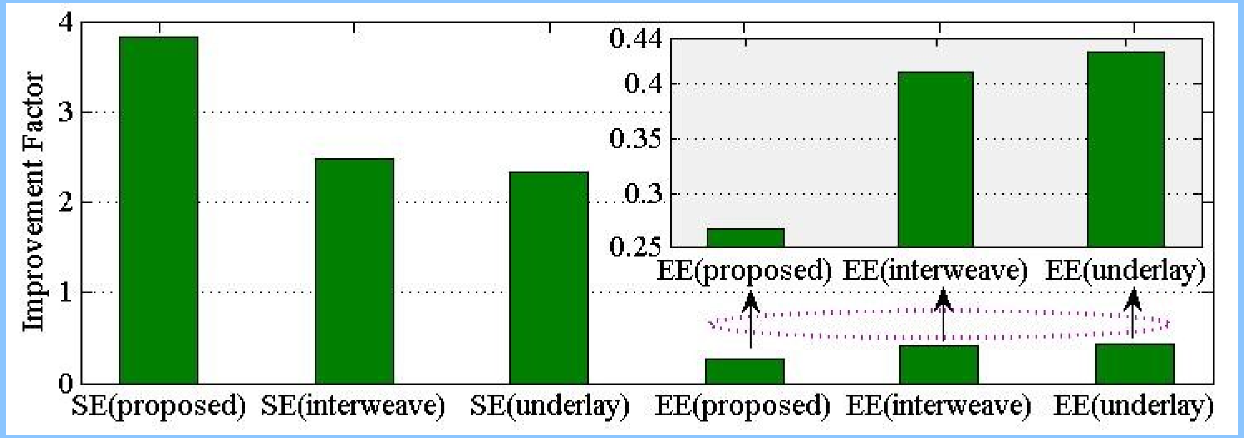


Figure 2. SE and EE improvement factors for an s-MNO (i.e., MNO 1) due to applying different techniques for a single building of SBSs.

- Using Table I, the **maximum amount of the shared spectrum** obtained by employing the proposed technique is **3 times** (interweave and underlay techniques each contributing **1.5 times**) the spectrum of MNO 1 **of *M* RBs**.
- This causes the proposed technique to increase the licensed spectrum of ***M* RBs to 4*M* RBs** for MNO 1.
- The **proposed technique** improves **SE by about 2.82 times**, whereas **EE by about 73%,** of MNO 1 as shown in Figure 2.

It can be found that with an increase in *l*, **SE increases linearly**, whereas **EE improves negative exponentially** for all techniques, and the proposed technique **outperforms all techniques** in terms of SE and EE

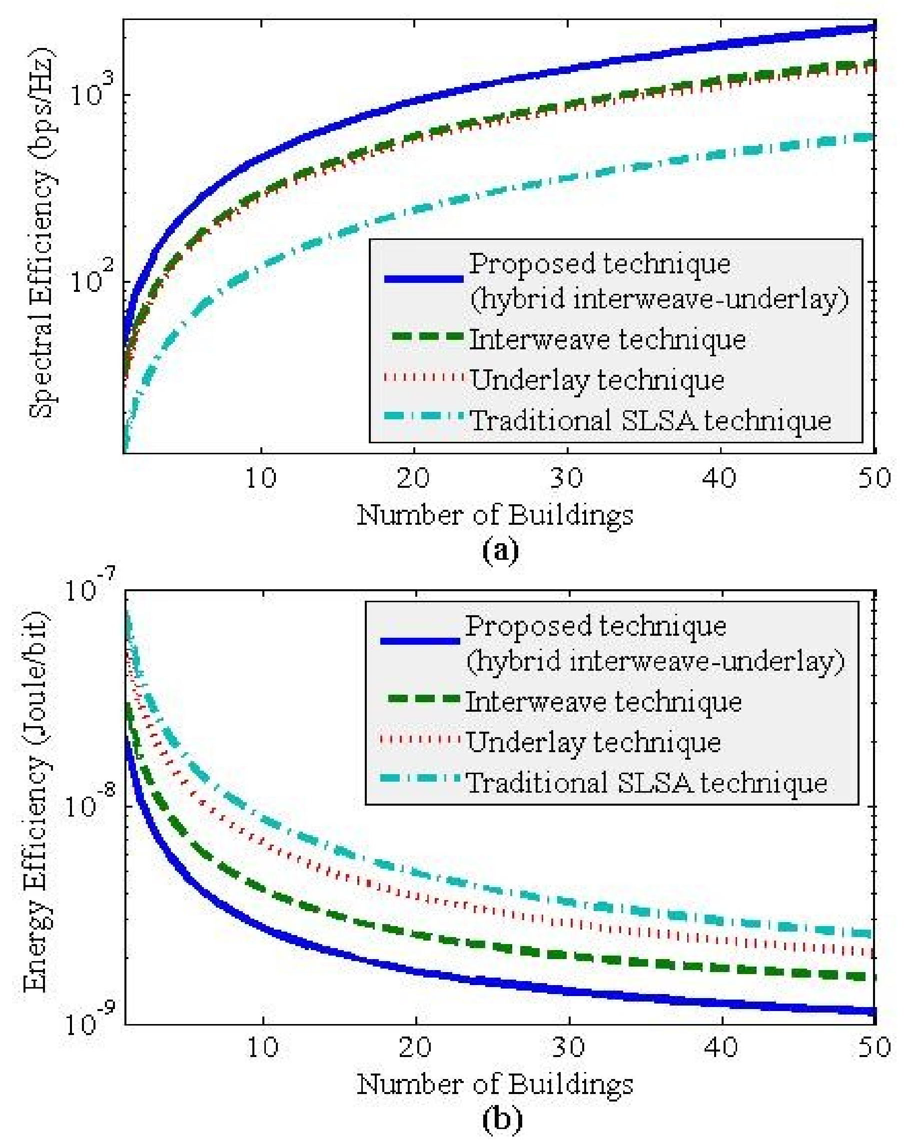


Figure 3. (a) SE and (b) EE performances for MNO 1 due to applying different techniques for multiple buildings of SBSs.

# Performance Results and Analysis

## Performance Comparison

Moreover, according to [18-19], it is expected that the 6G mobile systems will require 10 times average SE (i.e., **270-370 bps/Hz**), as well as 10 times average EE (i.e., **0.3$\mu$J/bit**), of 5G mobile systems [20-22].

Using **Figure 3,** the values of *l* that satisfy both SE and EE requirements for 6G mobile systems are **9, 13, 14, and 32**, respectively for the proposed **hybrid, interweave, underlay, and SLSA** techniques.

Hence, the proposed hybrid interweave-underlay technique **can satisfy both SE and EE requirements** for 6G by reusing the whole mmWave spectrum of MNO 1 to its small cells of **roughly 31%, 36%, and 72% less number of buildings** than that required by the traditional **interweave, underlay, and SLSA techniques,** respectively.

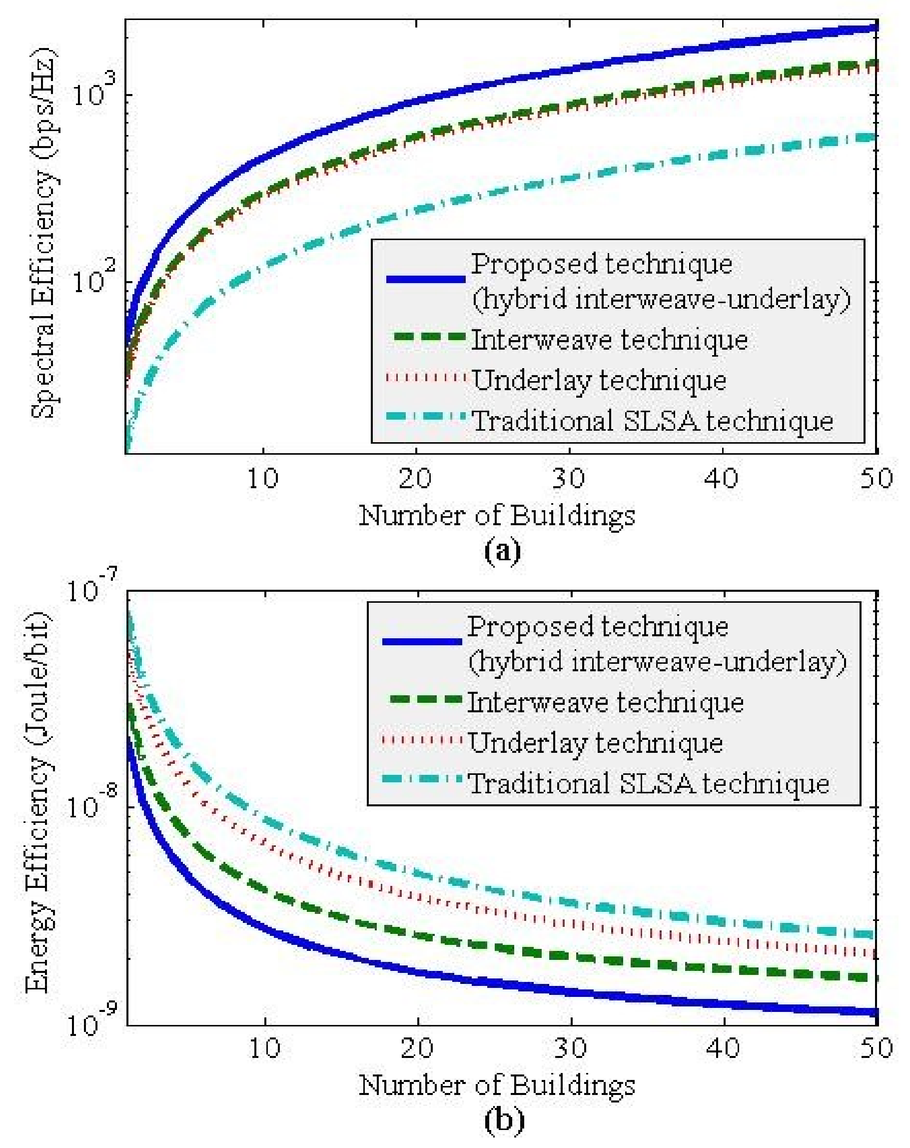


Figure 3. (a) SE and (b) EE performances for MNO 1 due to applying different techniques for multiple buildings of SBSs.

# Conclusion

**Addresses**

In this paper, we have **proposed a hybrid interweave-underlay spectrum access technique** to share the licensed 28 GHz mmWave spectrum of one MNO with small cells in a building of another MNO.

We have derived average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) performances for the proposed technique and carried out numerical and simulation results and analyses for MNO 1 of a country consisting of four MNOs.

**Findings**

- The proposed technique can improve SE by about 2.82 times, whereas EE by about 73%, of MNO 1 as compared to that of the traditional Static Licensed Spectrum Allocation (SLSA) technique.
- Further, the proposed technique can satisfy both SE and EE requirements for 6G mobile systems by reusing the mmWave spectrum of MNO 1 to its small cells of roughly 31%, 36%, and 72% less number of buildings than that required by the traditional interweave, underlay, and SLSA techniques, respectively.

**Further Studies**

The proposed technique can be investigated further to address **numerous crucial issues**, including

- millimeter-wave bands other than 28 GHz, such as 26 GHz, 38 GHz, and 60 GHz,
- non-LOS path loss models,
- directional millimeter-wave antennas,
- spectrum sensing mechanisms and control signaling overhead,
- implementation complexity analysis,
- burst traffic characteristics,
- random deployments of indoor UEs, as well as
- serving more than one UE simultaneously by a single small cell in a building.

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# End of the Presentation

Thank You …