Licensed Millimeter-Wave Spectrum Allocation and Reuse in Indoor Environments

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***Abstract*—In this paper, by exploiting the frequency domain, we propose a Countrywide Millimeter-Wave (mmWave) Spectrum Allocation and Reuse (CoMSAR) technique that allocates and reuses spatially the countrywide 28 GHz spectrum to each Mobile Network Operator (MNO) of a country to operate its small cells per floor in a building. An interference management scheme is developed to avoid Co-Channel Interference (CCI) in each apartment. We model user statistics per small cell and interferer statistics per apartment and formulate the optimal amount of spectrum for each MNO. We derive average capacity, Spectral Efficiency (SE), Energy Efficiency (EE), and Cost Efficiency (CE) for the proposed technique and the traditional Static Licensed Spectrum Allocation (SLSA) technique allocating an equal amount of spectrum to each MNO. By varying CCI and spectrum reuse, extensive numerical and simulation results and analyses are carried out for a country consisting of four MNOs, i.e., MNOs 1, 2, 3, and 4 with a subscriber base of, respectively, 40%, 30%, 20%, and 10% of the countrywide subscribers. It is shown that CoMSAR with no CCI provides 2.5 times higher average capacity, SE, EE, and CE than that with the maximum CCI. However, with regard to SLSA, it improves the average capacity, SE, EE, and CE of MNO 1 by 300%, 165%, 75%, and 60%, respectively, with no CCI, each of which decreases to the minimum value when CCI is the maximum. Further, we show that CoMSAR can satisfy SE and EE requirements for sixth-generation (6G) mobile systems by reusing the countrywide 28 GHz spectrum to small cells of MNO 1 of about 61.2% less number of single-floor buildings with no CCI, whereas 6.4% less number of single-floor buildings with the maximum CCI, than that required by SLSA. Finally, we discuss the benefits and point out key issues of CoMSAR for further studies.**

Keywords*—6G; 28 GHz; countrywide; millimeter-wave; mobile network; spectrum allocation; spectrum reuse; indoor; small cell.

I. INTRODUCTION

A. Background

The high capacity and data rate requirements for the existing mobile networks impose a demand for the massive radio spectrum availability on a Mobile Network Operator (MNO). Due to this reason, the traditional model (Foster [2] for allocating a portion of the licensed spectrum statically in an exclusive manner for a long time has no longer been considered effective to address the ever-increasing high capacity and data rate demands. Though these requirements have been increased over time, the availability of the spectrum for an MNO has not increased correspondingly, resulting in the scarcity of the radio spectrum. In this regard, spectrum allocation and spectrum exploitation can play a vital role in addressing the spectrum scarcity for an MNO in a country. Spectrum allocation techniques describe how the spectrum specified for a country is allocated to its MNOs. The usefulness of a spectrum allocation technique is affected by factors, such as the amount and duration of the allocated spectrum to an MNO, as well as the user traffic demand of an MNO (Saha [3]). By carefully allocating the spectrum specified for a country among its MNOs, the available amount of spectrum for an MNO can be extended considerably. Furthermore, by exploiting the available spectrum for an MNO in space, for example, the utilization of the spectrum can be increased. Accordingly, the spatial reuse of the spectrum to small cells, particularly in a 3-Dimensional (3D) space, e.g., a multistory building, is considered an effective approach to increase the utilization of the available spectrum.

B. Related Work

Numerous research works have already addressed the issues of spectrum allocation, as well as spectrum exploitation. For example, Yan et al. [4] have proposed methods for the dynamic spectrum allocation in cognitive radio systems, and Wei et al. [5] have presented a system-level dynamic frequency spectrum allocation scheme based on central heterogeneous network architecture. Using the carrier aggregation technique, Shajaiah et al. [6] have considered the optimization of resource allocation, whereas, based on the access mechanism, Liu et al. [7] have proposed a joint subcarrier and power allocation method. Further, Kim et al. [8] have introduced the functionalities required for entities related to the spectrum allocation to propose a spectrum allocation algorithm in multiple network operators' scenarios. Moreover, Kim et al. [9] have introduced and formulated the problem of the optimum spectrum allocation in cognitive radios. Furthermore, Gu [10] has proposed a new dynamic spectrum allocation algorithm to resolve channel conflict problems in channel switching and Bhuiyan et al. [11] have developed a traffic-load-aware channel allocation mechanism for secondary users.

Regarding the spectrum exploitation by means of reusing the available spectrum, an analytical model has been proposed by Saha and Aswakul [12] to reuse the microwave spectrum, as well as by Saha [13] to reuse the 28 GHz millimeter-wave (mmWave) spectrum, in a 3D building of small cells. Likewise, Saquib et al. [14] have investigated a number of Fractional Frequency Reuse (FFR) schemes, whereas Hasan et al. [15] have proposed the dynamic fractional frequency reuse (DFFR) method to reduce the inter-cell interference. Moreover, Saha [16] has proposed a technique to reuse the same spectrum for small cells deployed in a building by forming 3D clusters of small cells. Besides, in time-varying channels, Yen et al. [17] have developed new FFR patterns for multi-cell orthogonal frequency-division multiple access systems with frequency or time division duplexing (FDD/TDD). Further, Lam et al. [18] have presented the performance of well-known frequency reuse algorithms in terms of, e.g., system throughput and average packet loss ratio.

C. Problem Statement and Contribution

However, unlike the traditional static licensed spectrum allocation that considers allocating a certain portion of the countrywide spectrum to an MNO, the whole countrywide mmWave spectrum can be allocated to each MNO to increase its spectrum. Besides, due to the high floor penetration loss, the same countrywide mmWave spectrum for each MNO can be exploited spatially on the inter-floor level to reuse more than once by small cells within a building. Hence, a technique that can employ both the spectrum allocation and spectrum exploitation means to the mmWave spectrum using in-building small cells to allocate the countrywide mmWave spectrum to each MNO, which is exploited further to be spatially reused by small cells in a building is considered promising to achieve high Spectral Efficiency (SE) and Energy Efficiency (EE) requirements for the next generation mobile networks.

Numerous studies have already attempted to achieve the expected SE and EE requirements for the Sixth-Generation (6G) mobile networks by employing the mmWave spectrum allocation and exploitation. For example, by exploiting the power domain, Saha [19] has proposed a hybrid interweave-underlay spectrum access and reuse technique to address the dynamic spectrum access and reuse of the countrywide 28 GHz mmWave spectrum to in-building small cells of each MNO in a country to achieve the required SE and EE of 6G. Unlike the countrywide mmWave spectrum, by exploiting the secondary spectrum trading, Saha [20] has proposed a dynamic exclusive-use spectrum access method to share partly and exclusively the licensed mmWave spectrum of one MNO to another in a country to address the SE and EE requirements for 6G. Further, Saha [21] has presented a technique for the 3D spatial reuse of 28 and 60 GHz mmWave spectra allocated to an MNO to its in-building small cells to achieve the expected SE and EE requirements for 6G networks. Unlike these existing literature works, in this paper, by exploiting the frequency domain, we propose A Countrywide MmWave Spectrum Allocation and Reuse (CoMSAR) technique that considers allocating and then reusing the massive 28 GHz mmWave spectrum specified countrywide to each MNO of a country to operate its small cells deployed on each floor in a multistory building to achieve the expected SE and EE requirements for 6G mobile networks.

D. Organization

In addressing the proposed technique, we first present the system architecture and the proposed technique, as well as develop a frequency-domain Co-Channel Interference (CCI) avoidance scheme, in Section II. In Section III, we model user statistics per small cell and interferer statistics per apartment. We also formulate an expression of the optimal amount of spectrum per MNO for an arbitrary number of MNOs in a country. In Section IV, we derive average capacity, SE, EE, and Cost Efficiency (CE) metrics for the proposed, as well as the traditional Static Licensed Spectrum Allocation (SLSA), techniques. In addition, we show mathematically the outperformance of the proposed technique over the SLSA technique. In Section V, extensive numerical and simulation results and analyses for an example scenario of a country consisting of four MNOs are carried out by varying the effect of the spectrum reuse and the co-channel interference of interferer user equipments (UEs) within each apartment. Moreover, we also show that the proposed technique with two extreme CCI scenarios, including no CCI and the maximum CCI, for an MNO can achieve the SE and EE requirements for 6G mobile systems. Section VI covers the discussion on the offered benefits of the proposed technique, as well as its further research directions. We conclude the paper in Section VII. In Appendix A, a list of acronyms/abbreviations is shown in Table A1, and a list of selected notations is given in Table A2.

E. Declaration

This paper is an extended version of the work Saha [1] presented at The Fifteenth International Conference on Systems and Networks Communications (ICSNC), Porto, Portugal, 2020. The conference article Saha [1] has been extended in two major directions as follows.

- With introducing the 60 GHz unlicensed spectrum, and
- Without introducing the 60 GHz unlicensed spectrum,

in addition to the 28 GHz licensed spectrum to each small cell such as in [1].

Particularly, we have reported the extended journal version of [1] concerning the allocation and reuse of both the 28 GHz licensed spectrum and 60 GHz unlicensed spectrum in [22], whereas the allocation and reuse of only the 28 GHz licensed spectrum in this paper.

The conference article Saha [1] is used as the basis of both journal versions (i.e., [22] and this paper), which differ mainly from Saha [1] in terms of enhancement of background material, expansion of discussion, and inclusion of new problems and results. More specifically, in both journal versions, as compared to Saha [1],

- We model user statistics per small cell and interferer statistics per apartment in a building.
- We show mathematically the outperformance of the proposed technique over the traditional SLSA technique.
- We also clarify the simulation parameters and assumptions used for generating the performance results.
- A more detailed performance evaluation and analysis than that in Saha [1] are carried out by varying the effect of the spectrum reuse (both vertically within a building and horizontally in between buildings) and the co-channel interference (by considering all possible number of interferer UEs within each apartment).
- Finally, in addition to the offered benefits of the proposed technique, we discuss its future research directions.

Note that due to an extended version of Saha [1] and being [22] published earlier than this paper, some materials in this paper, in terms of, e.g., text, equations, figures, tables, notations, and abbreviations, may be found merged with that in [22] by citing [22]. Finally, this paper is written such that the readers will find it self-contained, detailed, and insightful in contrast to its conference version Saha [1].

II. System Architecture, Proposed Technique and Interference Management

A. System Architecture

Figure 1 shows the system architecture consisting of four MNOs, defined as MNO 1, MNO 2, MNO 3, and MNO 4, operating in a country. We assume that all MNOs have similar system architectural features including three types of Base Stations (BSs), namely macrocell BSs (MBSs), Picocell BSs (PBSs), and Small Cell BSs (SBSs). Hence, for simplicity in evaluating the performances, the detailed architecture of only one MNO, i.e., MNO 1, is shown in Figures 1(a) and 1(b). SBSs are deployed only within 3-dimensional multistory buildings (Figure 1(b)). Both SBSs and PBSs are located within the coverage of an MBS. All macrocell UEs per MBS are served either by the MBS itself or any PBSs. Due to the favorable characteristics, MBSs and PBSs operate at a low-frequency band, i.e., 2 GHz, whereas all in-building SBSs operate at the 28 GHz mmWave band (Figure 1(a)).

We consider that each MNO is given access to the countrywide 28 GHz mmWave spectrum to extend its spectrum at all times by enforcing the frequency-domain CCI management scheme, as shown in Figure 1(c). Given that CCI for an MNO o increases with an increase in the number of UEs of other MNOs $\boldsymbol{O}\backslash o$ (Figure 1(c) for MNO 1), Figure 1(c) shows all possible CCI scenarios for a small cell in an apartment of MNO 1 on a floor based on the presence of UEs of other MNOs $\boldsymbol{O}\backslash o$ within the same apartment of a building. For simplicity, CCI scenarios are shown for a single small cell each serving one UE at a time in an apartment on a floor. Besides, the penetration loss of a typical reinforced concrete floor in the 28 GHz mmWave spectrum is about 55 dB for the first floor [23][24][25]. Hence, by exploiting the high floor penetration loss of the 28 GHz mmWave spectrum, on top of the spectrum extension by allocating the countrywide massive 28 GHz spectrum to each MNO, we consider the spectrum exploitation by reusing the same countrywide spectrum to SBSs of each MNO on each floor of a building to increase spectral utilization (Figures 1(b) and 1(c)). We propose a technique for the spectrum allocation and the spectrum exploitation of the countrywide 28 GHz spectrum to each MNO in what follows.

B. Proposed Technique

We propose a countrywide mmWave spectrum allocation and reuse (CoMSAR) technique to extend the available spectrum for an MNO and to increase its utilization as follows.

Each MNO of a country is assigned with the massive 28 GHz mmWave spectrum specified countrywide, which is reused further, to operate its small cells deployed on each floor in a building at the cost of paying the spectrum licensing fee subject to avoiding CCI. The amount of the spectrum licensing fee for an MNO is updated corresponding to the change in its number of subscribers at each license renewal term t_{rnw}.

In this regard, for the 28 GHz mmWave spectrum allocation, each MNO is allocated to the countrywide 28 GHz mmWave spectrum by the National Regulatory Agency (NRA) or any third party for a term t_{rnw}. For the 28 GHz mmWave spectrum reuse, each MNO can exploit the high floor penetration loss of a multistory building at mmWave such that the allocated countrywide full 28 GHz mmWave spectrum can be reused to its SBSs deployed on each floor due to the insignificant or no CCI generated between adjacent floors (Figure 1(b)). This results in reusing the allocated countrywide spectrum to an MNO more than once to its SBSs within a multistory building and, hence, improving the countrywide 28 GHz mmWave spectrum utilization.

Each MNO pays the licensing fee to the NRA, which is defined by the administration based on the ratio of its actual number of subscribers to the sum of the total number of subscribers of all MNOs countrywide at t_{rnw}. Hence, the proposed technique can help overcome the lack of a sufficient amount of spectrum of an MNO to serve the necessary demand of its users, as well as address the issue of the under-utilized or unused spectrum of other MNOs, which in turn improve the overall countrywide spectrum utilization. Also, an MNO pays the licensing fee only for the amount of spectrum that it uses at any term t_{rnw} (i.e., in accordance with its number of users).

C. Co-channel Interference Management

Since all MNOs consider operating in-building small cells at the same countrywide 28 GHz mmWave spectrum, CCI occurs when small cell UEs of more than one MNO on the same floor in a building are scheduled to the same frequency simultaneously. Such CCI can be avoided by allocating UEs orthogonally in the frequency domain [26]. More specifically, UEs of MNOs located on the same floor in a building are allocated orthogonally to different parts of the countrywide 28 GHz mmWave spectrum, as shown in Figure 2. Hence, UEs of not more than one MNO can be allocated to the same frequency in any Transmission Time Interval (TTI). The existence of an interfering UE can be detected either by the small cell or the small cell UE itself using any conventional spectrum sensing techniques.

III. Mathematical Analysis

A. Modeling User Statistics per Small Cell

Like [22], we first model user statistics per small cell in this section. We are interested in finding the number of users per small cell of an MNO o in an apartment for an observation time Q. Let $U_s \in \boldsymbol{U}_s = \left\{0, 1, 2, ..., U_{s,\max}\right\}$ denote the number of UEs served by an SBS s of an MNO o at any time t. According to [27][28], sessions or call arrivals can be modeled as a Poisson process. Hence, the traffic activity of a small cell UE served by an in-building SBS can be modeled as an exponentially distributed continuous-time Poisson process. Since given the present state, the future state is independent of the past state, the traffic activity of a UE can be modeled as a two-state Markov chain where the off-state traffic activity to on-state traffic activity transition rate of a UE is denoted by λ and the on-state traffic activity to off-state traffic activity transition rate is denoted by μ.

Let $p(0), p(1), p(2), \cdots, p(U_{s,\max})$ denote the on-state probabilities of an SBS s (corresponding to the number of active UEs U_s) in an apartment. The values of these probabilities can be found following the Birth-Death process [27] as shown in Figure 3. Let λ_{U_s} and μ_{U_s} denote, respectively, the birth rate and the death rate. Then, according to [29] [30], the followings hold.

$$\lambda_{U_s} = \begin{cases} \left(U_{s,\max} - U_s\right)\lambda, & 0 \le U_s \le U_{s,\max} \\ 0, & \text{otherwise} \end{cases}$$

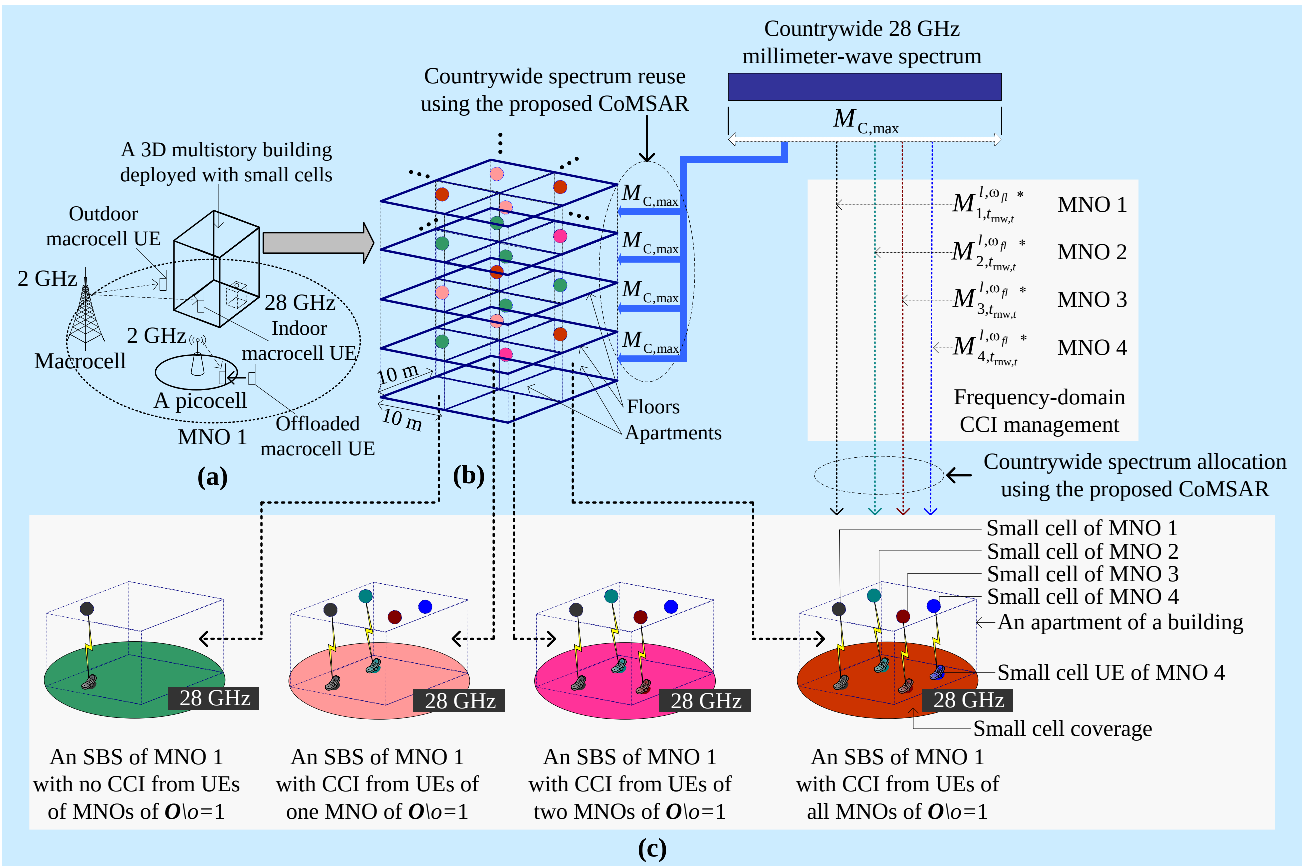


Figure 1. A system architecture consisting of four MNOs countrywide.

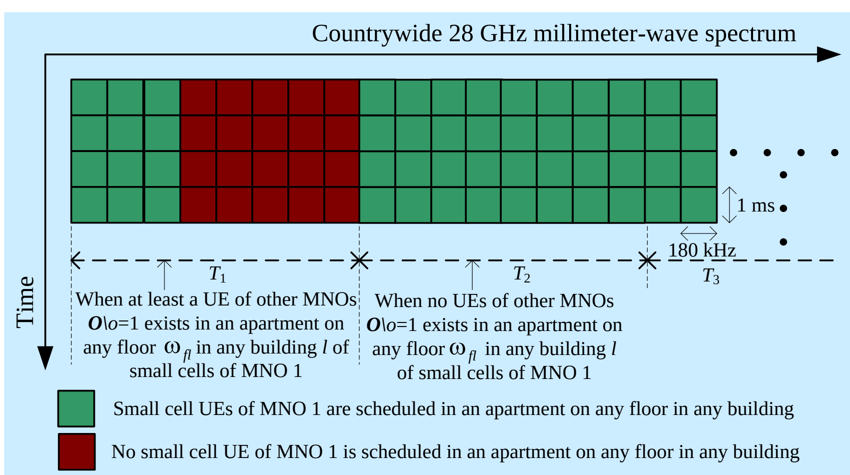


Figure 2. The frequency-domain CCI avoidance technique for UEs of MNO 1 in an apartment on any floor ω_{fl} in a building l. T_1, T_2, and T_3 define arbitrary and equal observation time intervals within $|\boldsymbol{T}| = Q$ [1].

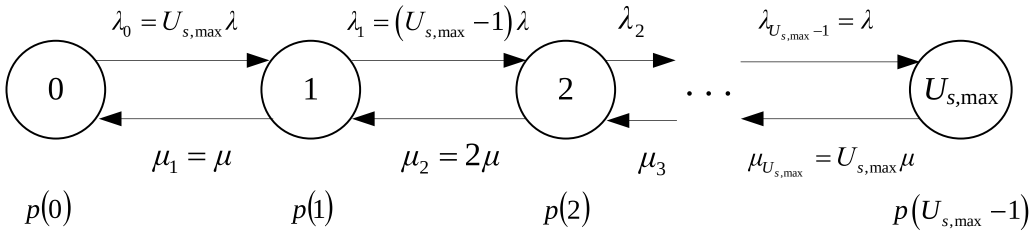


Figure 3. Occupancy or traffic in-progress state diagram for UEs per small cell in an apartment.

$\mu_{U_s} = U_s \times \mu$

Hence, the probability of any U_s can be given by,

$$p(U_s) = p(0)\left((\lambda/\mu)^{U_s} \times \binom{U_{s,\max}}{U_s}\right) \quad (1)$$

But, $\sum_{U_s=0}^{U_{s,\max}} p(U_s) = 1$ (2)

Then, using (1) and (2), the following can be obtained.

$$p(0) = 1/(1 + (\lambda/\mu))^{U_{s,\max}}$$

Now from (1), we can find the following. In other words, the probability that U_s number of UEs are served by an SBS s is given by,

$$p(U_s) = \frac{U_{s,\max}!}{U_s!(U_{s,\max} - U_s)!} \times (\lambda/\mu)^{U_s} \times \frac{1}{(1 + (\lambda/\mu))^{U_{s,\max}}} \quad (3)$$

Hence, the *expected value* of the number of UEs served simultaneously at any time t is then given by,

$$E[U_s] = \sum_{U_s=0}^{U_s=U_{s,\max}} (U_s \times p(U_s)) \quad (4)$$

Note that, since the rate of arrival of UEs to any in-building SBS s is relatively low due to the small coverage, the value of U_s is small in the *Poisson* distribution of small cell UEs [22]. In other words, smaller values of U_s are more probable than the larger ones such that the distribution of small cell UEs of an SBS lies mostly toward the left of the curve.

B. *Optimal Amount of Spectrum per MNO*

Let O denote the maximum number of MNOs of a country such that $o \in \boldsymbol{O} = \{1, 2, ..., O\}$. Let $S_{\mathrm{F},o}$ denote the total number of small cells of an MNO o in any building $l \in \boldsymbol{L} = \{1, 2, 3, ..., L\}$ such that $s_{x,o} \in \boldsymbol{S_{x,o}} = \{0, 1, 2, ..., S_{\mathrm{F},o}\}$. Denote $M_{\mathrm{C,max}}$ as the countrywide total amount of mmWave spectrum defined in terms of the number of Resource Blocks (RBs) where an RB is equal to 180 kHz. Assume that $E[U_{s,o}] = 1$, i.e., each small cell $s_{x,o}$ of an MNO o can serve the maximum of one UE at a time.

Let $N_{o,t_{\mathrm{rnw}}}$ denote the total number of subscribers of an MNO o such that $\sum_o^O N_{o,t_{\mathrm{rnw}}} \le N_{\mathrm{C,\,max},t_{\mathrm{rnw}}}$ where $N_{\mathrm{C,\,max},t_{\mathrm{rnw}}}$ denotes the maximum number of subscribers of a country at term t_{rnw}. Also, UEs of not more than one MNO o on the same floor ω_{fl} can be served at the same RBs in any TTI in a building l. The amount of spectrum allocated to UEs of an MNO o on a floor ω_{fl} in a building l at term t_{rnw} in TTI t is defined as follows.

The amount of spectrum allocated to UEs of an MNO o on any floor ω_{fl} in a building l at term t_{rnw} is defined in accordance with the ratio of the number of subscribers $N_{o,t_{\mathrm{rnw}}}$ of the MNO o to the sum of the total number of subscribers $N_{t_{\mathrm{rnw}},t}^{l,\omega_{fl}}$ of all MNOs O corresponding to the same floor ω_{fl} in the building l in any TTI t at term t_{rnw}.

Note that the radio spectrum is not free of cost. Hence, licensing more spectrum causes an increase in the cost of an MNO. Moreover, as the total amount of the spectrum specified for a country is fixed, licensing more spectrum by one MNO causes the scarcity of the required spectrum by another MNO in a country, resulting in degrading the quality-of-service (QoS). This problem can be addressed if each MNO takes the license of the amount of the spectrum as low as possible corresponding to its actual number of subscribers so that the issue of the under-utilized or unused spectrum by one MNO, as well as the lack of a sufficient amount of spectrum for another MNO, to serve its necessary user demand can be addressed.

Since each MNO favors minimizing the cost of licensing spectrum while ensuring to serve its user demands adequately to retain QoS, we consider a minimization problem for allocating the countrywide mmWave spectrum to each MNO to increase the overall countrywide mmWave spectrum utilization. Hence, the optimal amount of licensed spectrum $M_{o,t_{\mathrm{rnw},t}}^{l,\omega_{fl}}$ in RBs for an MNO $o \in \boldsymbol{O}$ on any floor ω_{fl} in a building l in TTI t at a renewal term t_{rnw} can be found by solving the following problem.

$$\min_{o\in\boldsymbol{O}} \quad M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}$$
$$\text{subject to} \quad \text{(a) } N_{o,t_{\mathrm{rnw}}} \Big/ N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t} = M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}} \Big/ M_{\mathrm{C,max}} \tag{5}$$
$$\text{(b) } \forall o \forall t_{\mathrm{rnw}} \sum_{o}^{O} N_{o,t_{\mathrm{rnw}}} \le N_{\mathrm{C,max},t_{\mathrm{rnw}}}$$

The solution to the above optimization problem can be expressed as follows and is given in Proof 1.

$$M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}{}^{*} = \left\lceil \left(\left(N_{o,t_{\mathrm{rnw}}} \Big/ \sum_{o=1}^{O} \left(1_{\nu_o}\left(N_{o,t_{\mathrm{rnw}}}\right) \times N_{o,t_{\mathrm{rnw}}} \right) \right) \times M_{\mathrm{C,max}} \right) \right\rceil \tag{6}$$

Proof 1: The solution to the optimization problem in (5) can be found as follows. In general, the number of subscribers of all MNOs is not the same at any t_{rnw}. Hence, assume that $N_{1,t_{\mathrm{rnw}}} > N_{2,t_{\mathrm{rnw}}} > ... > N_{O,t_{\mathrm{rnw}}}$ at t_{rnw} such that the constraint 5(b) is satisfied. Since a UE of any MNO $\boldsymbol{O}\backslash o$ in any TTI may not exist on any floor ω_{fl} in a building l of small cells of an MNO o, $N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t}$ can be expressed for O=4 as

$$N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t} = \sum_{o=1}^{O} \left(1_{\nu_o}\left(N_{o,t_{\mathrm{rnw}}}\right) \times N_{o,t_{\mathrm{rnw}}} \right) \tag{7}$$

where $\nu_o \in \left\{ N_{1,t_{\mathrm{rnw}}}, N_{2,t_{\mathrm{rnw}}}, N_{3,t_{\mathrm{rnw}}}, N_{4,t_{\mathrm{rnw}}} \right\}$. $1(\cdot)$ defines that $1(\cdot)=1$ if $N_{o,t_{\mathrm{rnw}}}$ exists in the set ν_o; otherwise, $1(\cdot)=0$.

Since the number of RBs is strictly an integer, using (7), and the constraint 5(a), the optimal value of $M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}$ is given by

$$M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}{}^{*} = \left(N_{o,t_{\mathrm{rnw}}} \Big/ N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t} \right) \times M_{\mathrm{C,max}}$$

$$M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}{}^{*} = \left\lceil \left(\left(N_{o,t_{\mathrm{rnw}}} \Big/ \sum_{o=1}^{O} \left(1_{\nu_o}\left(N_{o,t_{\mathrm{rnw}}}\right) \times N_{o,t_{\mathrm{rnw}}} \right) \right) \times M_{\mathrm{C,max}} \right) \right\rceil \quad \blacksquare$$

Note that if a UE of any MNO $\boldsymbol{O}\backslash o$ in any TTI t on any floor ω_{fl} in a building l does not exist, then $N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t} = N_{o,t_{\mathrm{rnw}}}$ in (7), which results in $M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}{}^{*} = M_{\mathrm{C,max}}$. This implies that the whole countrywide 28 GHz mmWave spectrum can be allocated in all TTIs t to UEs of small cells of an MNO o on any floor ω_{fl} in a building l. The same process described above is applicable for all MNOs $o \in \boldsymbol{O}$ at each renewal term t_{rnw} to update $M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}{}^{*}$ in any TTI t to avoid CCI [22]. Hence, using (6), the countrywide 28 GHz spectrum can be reused to small cells of each MNO o on any floor ω_{fl} in a building l at the cost of paying the licensing fee based on $N_{o,t_{\mathrm{rnw}}}$ of the corresponding MNO o at t_{rnw} with respect to that of other MNOs $\boldsymbol{O}\backslash o$ to improve countrywide 28 GHz mmWave spectrum utilization. Further, the higher the number of subscribers $N_{o,t_{\mathrm{rnw}}}$ of an MNO o at term t_{rnw}, the greater the amount of mmWave spectrum $M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}$ allocated to MNO o on any floor ω_{fl} in a building l in any TTI t at term t_{rnw}.

C. Modeling Interferer Statistics per Apartment

Following [22], recall that we assume $E\left[U_{s,o}\right]=1$ for each SBS of each MNO o within each apartment of any building. Since the arrival of a UE to any SBS in an apartment can be modeled as a Poisson process, under the above assumption, the presence of the number of interferer UEs in each apartment can be expressed following the same procedure presented for modeling the user statistics per small cell in Section III(A). In doing so, let $U_k \in \boldsymbol{U_k} = \left\{0,1,2,...,U_{k,\max}\right\}$ denote the number of interferer UEs served by each SBS of MNOs $\boldsymbol{O}\backslash o$ in any TTI t for an SBS s of MNO o, where $U_{k,\max} = O-1$. Then, the probability of U_k number of interferer UEs for an SBS s of MNO o in an apartment is given by,

$$p\left(U_k\right) = \frac{U_{k,\max}!}{U_k!\left(U_{k,\max}-U_k\right)!} \times \left(\lambda/\mu\right)^{U_k} \times \frac{1}{\left(1+\left(\lambda/\mu\right)\right)^{U_{k,\max}}} \tag{8}$$

Hence, the *expected value* of the number of interferer UEs served simultaneously at any time t in an apartment for an SBS s of MNO o is then given by,

$$E\left[U_k\right] = \sum_{U_k=0}^{U_k=U_{k,\max}} \left(U_k \times p\left(U_k\right)\right) \tag{9}$$

From (9), it can be found that the maximum amount of spectrum is allocated to an MNO o when no interferer UEs of MNOs $\boldsymbol{O}\backslash o$ exist within an apartment on any floor (i.e., $E\left[U_k\right]=0$). Likewise, the minimum amount of spectrum is allocated to an MNO o when each interferer UE of MNOs $\boldsymbol{O}\backslash o$ exist within each apartment on any floor, i.e., $E\left[U_k\right]=\left(U_{k,\max}-1\right)$ [22].

IV. Performance Metrics Estimation and Analysis

A. Performance Metrics

Let $S_{\mathrm{M},o}$ denote the number of macrocells, and $S_{\mathrm{P},o}$ denotes the number of picocells per macrocell of an MNO o. Also, let $\boldsymbol{T}$ denote the simulation run time with the maximum time of Q (in time steps each lasting 1 ms) such that $\boldsymbol{T}$= {1, 2, 3,…,Q}. Let P_{MC}, P_{PC}, and P_{SC} denote, respectively, the transmission power of a macrocell, a picocell, and a small cell of an MNO o. Using Shannon's capacity formula, a link throughput at RB=i in TTI=t for an MNO o at t_{rnw} in bps per Hz is given by [31][32]

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

where β denotes the implementation loss factor.

Let $M_{\mathrm{MBS},o}$ denote the spectrum in RBs of a macrocell for an MNO *o*. Then, the total capacity of all macrocell UEs for an MNO *o* at t_{rnw} can be expressed as

$$\sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{\mathrm{MBS},o}} \sigma_{t,i,o}^{t_{\mathrm{rnw}}} \left(\rho_{t,i,o}^{t_{\mathrm{rnw}}}\right) \quad (11)$$

where σ and ρ are responses over $M_{\mathrm{MBS},o}$ RBs of all macro UEs in $t \in \boldsymbol{T}$ for an MNO *o* at t_{rnw}. If all SBSs $s_{\omega_{fl},o}$ on any floor ω_{fl} in a building *l* of an MNO *o* serves simultaneously in all TTI $t \in \boldsymbol{T}$, then, the aggregate capacity served by an SBS, all SBSs per floor ω_{fl}, as well as all SBSs on all floors ω_{FL} in a building *l*, of an MNO *o* at a renewal term t_{rnw} are given respectively by

$$\sigma_{\mathrm{FD},o,l,s_{x,o}}^{t_{\mathrm{rnw}},\omega_{fl}} = \sum_{t \in \boldsymbol{T}} \sum_{i=1}^{M_{o,t_{\mathrm{rnw}},t}^{l,\omega_{fl}}{}^{*}} \sigma_{t,i,o}^{t_{\mathrm{rnw}}} \left(\rho_{t,i,o}^{t_{\mathrm{rnw}}}\right) \quad (12)$$

$$\sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{fl}} = \sum_{s_{x,o}=1}^{S_{\omega_{fl},o}} \sigma_{\mathrm{FD},o,l,s_{x,o}}^{t_{\mathrm{rnw}},\omega_{fl}} \quad (13)$$

$$\sigma_{\mathrm{FD},o,l}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}} = \sum_{\omega_{fl}=1}^{\omega_{\mathrm{FL}}} \sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{fl}} \quad (14)$$

Due to a short distance between a small cell UE and its SBS and a low transmission power of an SBS, we assume similar indoor signal propagation characteristics for all *L* buildings per macrocell for an MNO *o* at t_{rnw}. Then, by linear approximation, the system-level average aggregate capacity, SE, and EE for all MNOs O countrywide at t_{rnw} for *l*=*L* can be given by

$$\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sum_{o=1}^{O} \left(\sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}} + \left(L \times \sigma_{\mathrm{FD},o,l}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}}\right)\right) \quad (15)$$

Since $\left(L \times \sigma_{\mathrm{FD},o,l}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}}\right) >> \sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}}$, roughly, (15) can be given by

$$\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \cong \sum_{o=1}^{O} \left(L \times \sigma_{\mathrm{FD},o,l}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}}\right) \quad (16)$$

$$\sigma_{\mathrm{FD,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \Big/ \left(\left(M_{\mathrm{C,max}} + \sum_{o=1}^{O} M_{\mathrm{MBS},o}\right) \times Q\right) \quad (17)$$

$$\sigma_{\mathrm{FD,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \left(\sum_{o=1}^{O} \left(\begin{array}{l} \left(L \times S_{\mathrm{F},o} \times P_{\mathrm{SC}}\right) \\ + \left(S_{\mathrm{P},o} \times P_{\mathrm{PC}}\right) + \left(S_{\mathrm{M},o} \times P_{\mathrm{MC}}\right) \end{array}\right)\right) \Big/ \left(\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \big/ Q\right) \quad (18)$$

where $S_{\mathrm{F},o} = \sum_{\omega_{fl}=1}^{\omega_{\mathrm{FL}}} s_{\omega_{fl},o}$ denotes the total number of SBSs in any building *l* for an MNO *o*.

However, in a traditional SLSA technique, a fair allocation of the licensed mmWave spectrum to each MNO in a country is assumed, i.e., each MNO is given license exclusively for an equal amount of the mmWave spectrum of *M* RBs such that for *O*=4, $M_{\mathrm{C,max}} = 4M$. Now, using (14)-(18), the system-level average capacity, SE, and EE for all MNOs O countrywide at t_{rnw} for *l*=*L* can be given by

$$\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sum_{o=1}^{O} \left(\sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}} + \left(L \times \sum_{\omega_{fl}=1}^{\omega_{\mathrm{FL}}} \sum_{s_{x,o}=1}^{S_{\omega_{fl},o}} \sum_{t \in \boldsymbol{T}} \sum_{i=1}^{M} \sigma_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}} \left(\rho_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}}\right)\right)\right) \quad (19)$$

$$\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \cong \sum_{o=1}^{O} \left(L \times \sum_{\omega_{fl}=1}^{\omega_{\mathrm{FL}}} \sum_{s_{x,o}=1}^{S_{\omega_{fl},o}} \sum_{t \in \boldsymbol{T}} \sum_{i=1}^{M} \sigma_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}} \left(\rho_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}}\right)\right) \quad (20)$$

$$\sigma_{\mathrm{SLSA,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \Big/ \left(\left(M_{\mathrm{C,max}} + \sum_{o=1}^{O} M_{\mathrm{MBS},o}\right) \times Q\right) \quad (21)$$

$$\sigma_{\mathrm{SLSA,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \left(\sum_{o=1}^{O} \left(\begin{array}{l} \left(L \times S_{\mathrm{F},o} \times P_{\mathrm{SC}}\right) + \\ \left(S_{\mathrm{P},o} \times P_{\mathrm{PC}}\right) + \left(S_{\mathrm{M},o} \times P_{\mathrm{MC}}\right) \end{array}\right)\right) \Big/ \left(\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \big/ Q\right) \quad (22)$$

Now, let ε_{C} denote the cost of the countrywide 28 GHz mmWave spectrum $M_{\mathrm{C,max}}$. Recall that an MNO *o* pays the spectrum licensing fee based on its number of subscribers $N_{o,t_{\mathrm{rnw}}}$ at t_{rnw} with respect to that of all MNOs $N_{\mathrm{C,\,max},t_{\mathrm{rnw}}}$. Assume that an MNO *o* pays the spectrum licensing fee of ε_o corresponding to $N_{o,t_{\mathrm{rnw}}}$ at t_{rnw} such that ε_o can be given by

$$\varepsilon_o = \left(N_{o,t_{\mathrm{rnw}}} / N_{\mathrm{C,\,max},t_{\mathrm{rnw}}}\right) \times \varepsilon_{\mathrm{C}} \quad (23)$$

Now, define Cost Efficiency (CE) as the cost required per unit achievable average capacity (i.e., per bps) such that the CE at term t_{rnw} can be expressed as follows for both techniques.

$$\varsigma_{\mathrm{FD,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} = \varepsilon_{\mathrm{C}} \big/ \sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \quad (24)$$

$$\varsigma_{\mathrm{SLSA,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} = \varepsilon_{\mathrm{C}} \big/ \sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \quad (25)$$

B. Performance Improvement

Hence, the factor representing an improvement in average capacity, SE, EE, and CE due to applying the proposed technique can be expressed respectively as follows.

$$\varsigma_{\mathrm{cap},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \big/ \sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \quad (26)$$

$$\varsigma_{\mathrm{SE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \sigma_{\mathrm{FD,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \big/ \sigma_{\mathrm{SLSA,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \quad (27)$$

$$\varsigma_{\mathrm{EE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \sigma_{\mathrm{FD,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \big/ \sigma_{\mathrm{SLSA,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \quad (28)$$

$$\varsigma_{\mathrm{CE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \varsigma_{\mathrm{FD,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} \big/ \varsigma_{\mathrm{SLSA,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} \quad (29)$$

In the following, we analyze the outperformance given by (26)-(29) of the proposed CoMSAR technique over the traditional SLSA technique in terms of average capacity, SE, EE, and CE [22]. In doing so, we consider the countrywide subscriber statistics of all MNOs on any floor ω_{fl} in a building l at a renewal term t_{rnw} in time t. Assume that the number of countrywide subscribers of MNO 1, MNO 2, MNO 3, and MNO 4 are, respectively, 10%, 20%, 30%, and 40% of the total number of subscribers in a country. Since the spectrum is allocated to any MNO o in proportionate to its number of subscribers, using (6), the allocated spectrum to MNO 1, MNO 2, MNO 3, and MNO 4, are given, respectively, by $M_{1,t_{\mathrm{rnw}},t}^{l,\omega_{fl}} = \left(0.1 \times M_{\mathrm{C,max}}\right)$, $M_{2,t_{\mathrm{rnw}},t}^{l,\omega_{fl}} = \left(0.2 \times M_{\mathrm{C,max}}\right)$, $M_{3,t_{\mathrm{rnw}},t}^{l,\omega_{fl}} = \left(0.3 \times M_{\mathrm{C,max}}\right)$, and $M_{4,t_{\mathrm{rnw}},t}^{l,\omega_{fl}} = \left(0.4 \times M_{\mathrm{C,max}}\right)$.

Hence, the total amount of the spectrum used to serve user demands of all MNOs when employing the proposed CoMSAR technique is given by,

$$M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{CoMSAR}} = \left(0.1 \times M_{\mathrm{C,max}}\right) + \left(0.2 \times M_{\mathrm{C,max}}\right) + \left(0.3 \times M_{\mathrm{C,max}}\right) + \left(0.4 \times M_{\mathrm{C,max}}\right)$$

$$M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{CoMSAR}} = M_{\mathrm{C,max}} \tag{30}$$

On the other hand, when employing the traditional SLSA technique, each MNO o is allocated to an equal amount of spectrum of $\left(0.25 \times M_{\mathrm{C,max}}\right)$. However, the number of subscribers of MNO 1, MNO 2, MNO 3, and MNO 4 are not the same such that each MNO does not need the same amount of spectrum. More specifically, since the amount of spectrum required to serve the user demand of any MNO varies in accordance with its number of subscribers, MNO 1, MNO 2, MNO 3, and MNO 4 can use, respectively, 10%, 20%, 25%, and 25% of $M_{\mathrm{C,max}}$. Hence, the total amount of the spectrum used to serve user demands of all MNOs when employing the SLSA technique is given by,

$$M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{SLSA}} = \left(0.1 \times M_{\mathrm{C,max}}\right) + \left(0.2 \times M_{\mathrm{C,max}}\right) + \left(0.25 \times M_{\mathrm{C,max}}\right) + \left(0.25 \times M_{\mathrm{C,max}}\right)$$

$$M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{SLSA}} = 0.8 \times M_{\mathrm{C,max}} \tag{31}$$

From (30) and (31), we can write the following.

$$M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{CoMSAR}} > M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{SLSA}} \tag{32}$$

Since the achievable capacity is directly proportional to the spectrum bandwidth, the following relation holds.

$$\sigma_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{CoMSAR}} > \sigma_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{SLSA}}$$

where $\sigma_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{CoMSAR}} \propto M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{CoMSAR}}$ and $\sigma_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{SLSA}} \propto M_{O,t_{\mathrm{rnw}},t}^{l,\omega_{fl},\mathrm{SLSA}}$ denote, respectively, the achievable capacities corresponding to the spectra in (30) and (31) due to employing the proposed CoMSAR and SLSA techniques.

Since SE is directly proportional, whereas EE and CE are inversely proportional, to the achievable capacity, using (17) and (21) for the SE, (18) and (22) for the EE, and (24) and (25) for the CE, it can be shown that the proposed CoMSAR technique provides better SE, EE, and CE performances than the traditional SLSA technique [22].

V. PERFORMANCE EVALUATION

A. *Default Parameter and Assumption*

Table I shows the default simulation parameters and assumptions used for evaluating the performance of the proposed technique for all MNOs O countrywide. The performance metrics are derived analytically for an arbitrary number of MNOs in a country and the evaluation is carried out for four MNOs (i.e., O=4) as an example scenario. The arrival of mobile traffic to a small cell is captured using the Poisson process to model the presence of UEs of MNOs within each apartment. Simulation assumptions and parameters used for the performance evaluation are in line with the recommendations from the standardization bodies such as the 3rd generation partnership project (3GPP) and International Telecommunication Union-Radiocommunication Sector (ITU-R).

For simplicity in analysis and finding a closed-form expression, we assume that each small cell of an MNO o can serve one UE at a time, i.e., $E\left[U_{s,o}\right] = 1$. Moreover, because of the favorable signal propagation characteristics in indoor environments and the availability of large spectrum bandwidth, we consider the 28 GHz millimeter-wave spectrum bands to serve high data rates within a short distance. However, all the macrocells and picocells are considered to operate at the 2 GHz band to provide large coverage and less number of hand-offs. Because high-frequency signals exhibit a low multi-path fading effect indoors, the Line-Of-Sight (LOS) large-scale signal propagation model is assumed for 28 GHz. Further, due to serving a UE at a short distance over a LOS channel by an SBS, similar signal propagation characteristics are considered within the same building, as well as between adjacent buildings.

Because of a high external wall penetration loss, low transmission power, and the existence of distance-dependent path loss for the distance in-between adjacent buildings for high-frequency signals, we assume an insignificant CCI effect from SBSs of one building to that of adjacent buildings resulting in reusing the same spectrum to SBSs within each building. Furthermore, we adopt the full buffer traffic model to consider serving user traffic at all times and the proportional fair scheduler to provide a balanced trade-off between the fairness and throughput performances. The performance results are generated by a simulator built using the computational tool MATLAB R2012b taking into account all parameters and assumptions stated above and given in Table I. Finally, the algorithm used to generate the performance results is given in Algorithm 1.

B. *Performance Result and Analysis*

The performance of the proposed technique is evaluated with regard to the traditional SLSA technique. We assume that MNO 1, MNO 2, MNO 3, and MNO 4 have the number of subscribers of 40%, 30%, 20%, and 10%, respectively, of the total number of subscribers countrywide $N_{C,\max,t_{rnw}}$ at any term t_{rnw} (Table I).

1) Impact of the CCI

The performance of the proposed technique is evaluated for UEs of MNO 1 by varying the number of co-channel interferer UEs of I_{CCI}=0 to I_{CCI}=3 of MNOs $\boldsymbol{O}\backslash o$=1 per apartment on a single floor of a building for a country with O=4 MNOs. Figure 4 shows the performance improvement of the proposed technique in terms of the average capacity, SE, EE, and CE with respect to that of the traditional SLSA technique. Note that we consider the worst-case scenario, i.e., $M_{1,t_{rnw},t}^{l,\omega_{fl}\ *}$ is minimum in (6), such that I_{CCI}=1 corresponds to a UE of MNO=2 with 30% of subscribers, and I_{CCI}=2 corresponds to UEs of MNO=2 and MNO=3 with 20% of subscribers. Whereas, I_{CCI}=0 and I_{CCI}=3 correspond to two extreme scenarios, including when no CCI occurs due to the absence of UEs of all other MNOs $\boldsymbol{O}\backslash o$=1, and when the maximum CCI occurs due to the presence of UEs of each MNO of $\boldsymbol{O}\backslash o$=1 on a floor in a building.

With no co-channel interferer UEs in any apartment (i.e., I_{CCI}=0), the maximum amount of full countrywide mmWave spectrum can be allocated to SBSs of MNO 1 on each floor in all TTIs. As I_{CCI} increases, the amount of allocated spectrum to MNO 1 decreases, and for the maximum co-channel interferer UEs, I_{CCI}=3, only 40% of the countrywide spectrum can be allocated to SBSs of MNO 1 on each floor. Hence, the spectrum allocated to SBSs of MNO 1 on each floor with I_{CCI}=0 is 2.5 times $(1/0.4)$ of the allocated spectrum I_{CCI}=3.

Since the achievable capacity depends directly on the amount of spectrum, the maximum and minimum average capacity, SE, EE, and CE for MNO 1 can be achieved, respectively, with I_{CCI}=0 and I_{CCI}=3 as shown in Figure 4. Moreover, Figure 4 also shows that the proposed technique with no CCI provides 2.5 times higher average capacity, SE, EE, and CE performances than that with the maximum CCI. Furthermore, with regard to the traditional SLSA, the proposed technique improves the average capacity, SE, EE, and CE of MNO 1 by 300%, 165%, 75%, and 60%, respectively with no co-channel interferer UEs, I_{CCI}=0. The improvement factors, however, decrease as I_{CCI} increases and get to a minimum when I_{CCI}=3. Hence, CCI plays a vital role in the overall performance of an MNO when allocated to the countrywide spectrum.

2) Effect of the Spectrum Reuse

Figures 5(a) and 5(b) show the effect of reusing the same countrywide spectrum both vertically to each floor of SBSs of MNO 1 in a multistory building and horizontally to each building over a macrocell coverage. As can be seen from Figure 5, the proposed technique provides better SE and EE performances than the traditional SLSA technique, with the variation of either ω_{FL}, or L, or both. Moreover, with an increase in the number of floors ω_{FL}, i.e., vertical reuse factor (RF), as well as the number of buildings L, i.e., horizontal RF, SE increases linearly, whereas EE increases negative exponentially, irrespective of the degree of CCI. Note, however, that since SE is affected additionally by the optimal amount of countrywide spectrum, the proposed technique with the maximum CCI provides insignificant SE while noticeable EE improvement over the traditional SLSA technique because of its higher average capacity performance, as shown in Figures 5(a) and 5(b).

Hence, the performance of the proposed technique is greatly influenced by the CCI, and a significant performance gain can be achieved when the aggregate CCI is limited to a low value. However, due to a small coverage of an indoor small cell and a low probability of co-existing all interferer UEs of MNOs $\boldsymbol{O}\backslash o$=1 within an apartment, the proposed technique can improve considerably the average SE and EE performances. Moreover, the impact of CCI can be compensated by increasing the RF. For example, the proposed technique with the maximum CCI for vertical RF=6 or more can provide better SE and EE performances than when operating under no CCI scenarios for vertical RF=1 for any horizontal RF.

C. Performance Comparison

According to [39][40], the future 6G mobile systems are expected to require 10 times average SE (i.e., 270-370 bps/Hz), as well as 10 times average EE (i.e., 0.3×10^{-6} Joules/bit), of that of 5G mobile systems [41][42]. Using Figure 5, Table II shows the variation in the required values of the vertical RF ω_{FL} and horizontal RF L when employing the traditional SLSA technique and the proposed technique with no CCI, as well as the maximum CCI, scenarios for each apartment on each floor of any building for MNO 1 to satisfy both the SE and EE requirements for 6G mobile systems.

From Table II, it can be found that the required SE and EE for 6G can be achieved by changing either vertical RF ω_{FL} or horizontal RF L such that their product, i.e., ($\omega_{FL}\times L$), defines the achievable SE and EE performances. Moreover, the proposed CoMSAR technique can satisfy both the SE of 370 bps/Hz and EE of 0.3 μJ/bit for 6G mobile systems by reusing (horizontally) the countrywide 28 GHz mmWave spectrum to small cells of MNO 1 of about 61.2% less number of single-floor (i.e., ω_{FL} =1) buildings (i.e., L=12) with no CCI, whereas 6.4% less number of single-floor buildings (i.e., L=29) with the maximum CCI, than that required by the traditional SLSA technique (i.e., L =31).

VI. Offered Benefits and Further Outlooks

A. Offered Benefits

The proposed technique benefits from a number of issues as follows. Unlike the traditional SLSA technique, the proposed technique ensures the availability of a large amount of spectrum by allocating the countrywide full (instead of a portion) mmWave spectrum to each MNO. Further, it provides an efficient spectrum utilization by allowing each MNO dynamic and flexible (instead of static and dedicated) access to the countrywide spectrum [22]. Furthermore, it allows an MNO to pay only for the amount of spectrum that it uses to serve its user demands (i.e., in proportionate with the number of its users) at any term t_{rnw}, resulting in reducing the cost per unit capacity (i.e., bps).

TABLE I. DEFAULT PARAMETERS AND ASSUMPTIONS

<table>
<tr><th colspan="3">Parameters and Assumptions</th><th colspan="2">Value</th></tr>
<tr><td colspan="3">28 GHz spectrum countrywide</td><td colspan="2">200 MHz</td></tr>
<tr><td colspan="3">Number of MNOs and subscribers</td><td colspan="2">4 and $N_{\mathrm{C,max}}$</td></tr>
<tr><td colspan="3">Number of subscribers for MNOs 1, 2, 3, and 4, respectively</td><td colspan="2">40%, 30%, 20%, and 10% of $N_{\mathrm{C,max}}$</td></tr>
<tr><td colspan="5">For each MNO</td></tr>
<tr><td colspan="3">E-UTRA simulation case[1,6]</td><td colspan="2">3GPP case 3</td></tr>
<tr><td colspan="3">Cellular layout[2,6], Inter-Site Distance (ISD)[1,2,6], transmit direction</td><td colspan="2">Hexagonal grid, dense urban, 3 sectors per macrocell site, 1732 m, downlink</td></tr>
<tr><td colspan="3">Carrier frequency[2,5,6]</td><td colspan="2">2 GHz Non-Line-Of-Sight (NLOS) for macrocells and picocells, 28 GHz LOS for all small cells</td></tr>
<tr><td colspan="3">Number of cells</td><td colspan="2">1 macrocell, 2 picocells, 280 small cells per building</td></tr>
<tr><td colspan="3">Total BS transmit power[1] (dBm)</td><td colspan="2">46 for macrocell[1,4], 37 for picocells[1], 19 for small cells[1,3,4]</td></tr>
<tr><td colspan="3">Co-channel small-scale fading model[1,3,5]</td><td colspan="2">Frequency selective Rayleigh for 2 GHz, none for 28 GHz</td></tr>
<tr><td rowspan="4">Path loss</td><td rowspan="2">MBS and a UE[1]</td><td>Outdoor macrocell UE</td><td colspan="2">PL(dB)=15.3 + 37.6 $\log_{10}R$, R is in m</td></tr>
<tr><td>Indoor macrocell UE</td><td colspan="2">PL(dB)=15.3 + 37.6 $\log_{10}R + L_{\mathrm{ow}}$, R is in m</td></tr>
<tr><td colspan="2">PBS and a UE[1]</td><td colspan="2">PL(dB)=140.7+36.7 $\log_{10}R$, R is in km</td></tr>
<tr><td colspan="2">SBS and a UE[1,2,5]</td><td colspan="2">$PL(\mathrm{dB}) = 61.38 + 17.97\log_{10}(d)$, d is in m</td></tr>
<tr><td colspan="3">Lognormal shadowing standard deviation (dB)</td><td colspan="2">8 for MBS[2] , 10 for PBS[1], and 9.9 for SBS[2,5]</td></tr>
<tr><td colspan="3">Antenna configuration</td><td colspan="2">Single-input single-output for all BSs and UEs</td></tr>
<tr><td colspan="3">Antenna pattern (horizontal)</td><td colspan="2">Directional (120^0) for MBS[1], omnidirectional for PBS[1] and SBS[1]</td></tr>
<tr><td colspan="3">Antenna gain plus connector loss (dBi)</td><td colspan="2">14 for MBS[2], 5 for PBS[1], 5 for SBS[1,3]</td></tr>
<tr><td colspan="3">UE antenna gain[2,3]</td><td colspan="2">0 dBi (for 2 GHz), 5 dBi (for 28 GHz, Biconical horn)</td></tr>
<tr><td colspan="3">UE noise figure[2,3] and UE speed[1]</td><td colspan="2">9 dB (for 2 GHz) and 10 dB (for 28 GHz), 3 km/hr</td></tr>
<tr><td colspan="3">Picocell coverage, number of macrocell UEs, and macrocell UEs offloaded to all picocells[1]</td><td colspan="2">40 m (radius), 30, 2/15</td></tr>
<tr><td colspan="3">Indoor macrocell UEs[1]</td><td colspan="2">35%</td></tr>
<tr><td colspan="3" rowspan="7">3D multistory building and SBS models (square-grid apartments)</td><td>Number of buildings</td><td>L</td></tr>
<tr><td>Number of floors per building</td><td>35</td></tr>
<tr><td>Number of apartments per floor</td><td>8</td></tr>
<tr><td>Number of SBSs per apartment</td><td>1</td></tr>
<tr><td>Number of SBSs per building</td><td>280</td></tr>
<tr><td>Area of an apartment</td><td>10×10 m^2</td></tr>
<tr><td>Materials used</td><td>Reinforced concrete</td></tr>
<tr><td colspan="3">Scheduler and traffic model[2]</td><td colspan="2">Proportional Fair and full buffer</td></tr>
<tr><td colspan="3">Type of SBSs</td><td colspan="2">Closed Subscriber Group femtocell BSs</td></tr>
<tr><td colspan="3">Channel State Information</td><td colspan="2">Ideal</td></tr>
<tr><td colspan="3">TTI[1] and scheduler time constant (t_c)</td><td colspan="2">1 ms and 100 ms</td></tr>
<tr><td colspan="3">Total simulation run time</td><td colspan="2">8 ms</td></tr>
</table>

taken [1]from [33], [2]from [34], [3]from [35], [4]from [36], from [5][37], from [6][38].

Algorithm 1. Proposed CoMSAR technique

```
Input: O=4, Q, t_rnw, N_{C,max,t_rnw} M, N_{o,t_mw}, M_{C,max}, S_{F,o}, P_MC, P_PC, P_SC, L_max, ω_FL
For L = {1, 2, 3, ..., L_max}
  For t={1, 2, 3,…,Q}
    For o ∈ O = {1, 2, ..., O}
      Find M^{l,ω_fl *}_{o,t_mw,t} using (6)
      Estimate Capacity, σ^{sys,t_mw}_{FD,cap,O}(L) and σ^{sys,t_mw}_{SLSA,cap,O}(L)
      Estimate SE σ^{sys,t_mw}_{FD,SE,O}(L) and σ^{sys,t_mw}_{SLSA,SE,O}(L)
      Estimate EE σ^{sys,t_mw}_{FD,EE,O}(L) and σ^{sys,t_mw}_{SLSA,EE,O}(L)
      Estimate CE ς^{sys,t_mw}_{FD,CE,O} and ς^{sys,t_mw}_{SLSA,CE,O}
    End
  End
End
```

13: Find improvement factors: $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{cap},O,\text{IF}}$, $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{SE},O,\text{IF}}$, $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{EE},O,\text{IF}}$, $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{CE},O,\text{IF}}$

14: **Output:** Display for MNO o=1: $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{cap},O,\text{IF}}$ $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{SE},O,\text{IF}}$ $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{EE},O,\text{IF}}$, $\varsigma^{\text{sys},t_{\text{mw}}}_{\text{CE},O,\text{IF}}$

15: **Plot:** For no CCI and maximum CCI for MNO o=1: $\sigma^{\text{sys},t_{\text{mw}}}_{\text{FD,SE},O}(L), \sigma^{\text{sys},t_{\text{mw}}}_{\text{SLSA,SE},O}(L), \sigma^{\text{sys},t_{\text{mw}}}_{\text{FD,EE},O}(L), \sigma^{\text{sys},t_{\text{mw}}}_{\text{SLSA,EE},O}(L)$

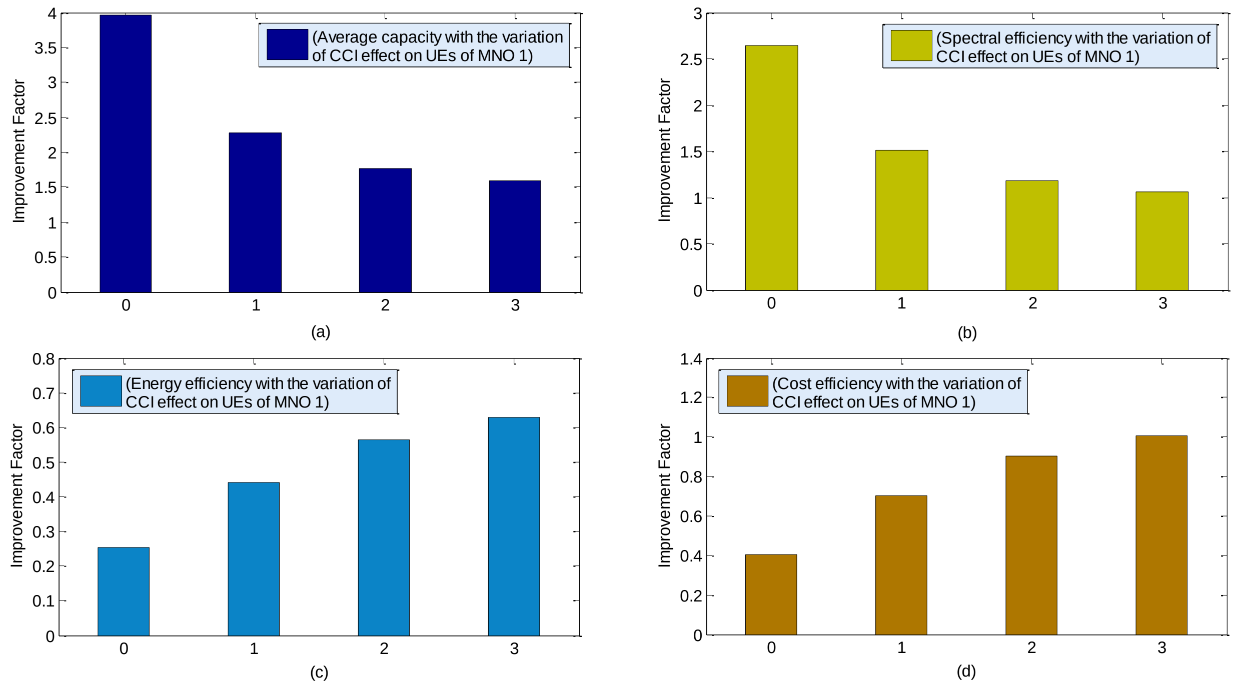
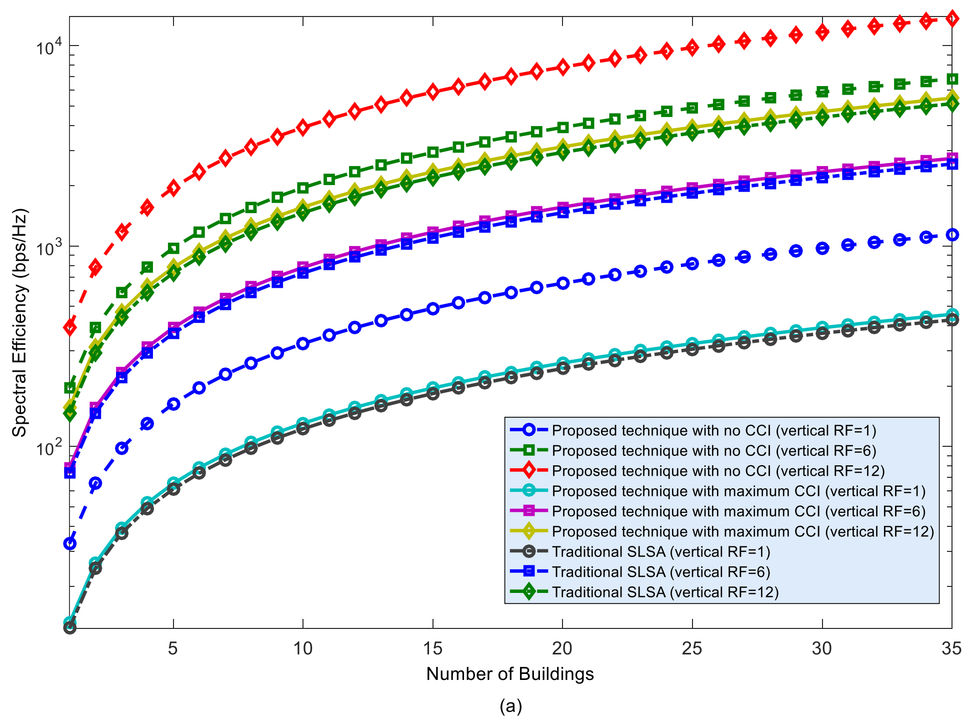


Figure 4. Performance improvement of the proposed CoMSAR technique with respect to that of the traditional SLSA technique due to the change in the number of co-channel interferer UEs of MNOs $\boldsymbol{O}\backslash o$=1 per apartment on a single floor of a building for UEs of MNO 1 of a country with O=4 MNOs. (a) average capacity, (b) spectral efficiency, (c) energy efficiency, and (d) cost efficiency.



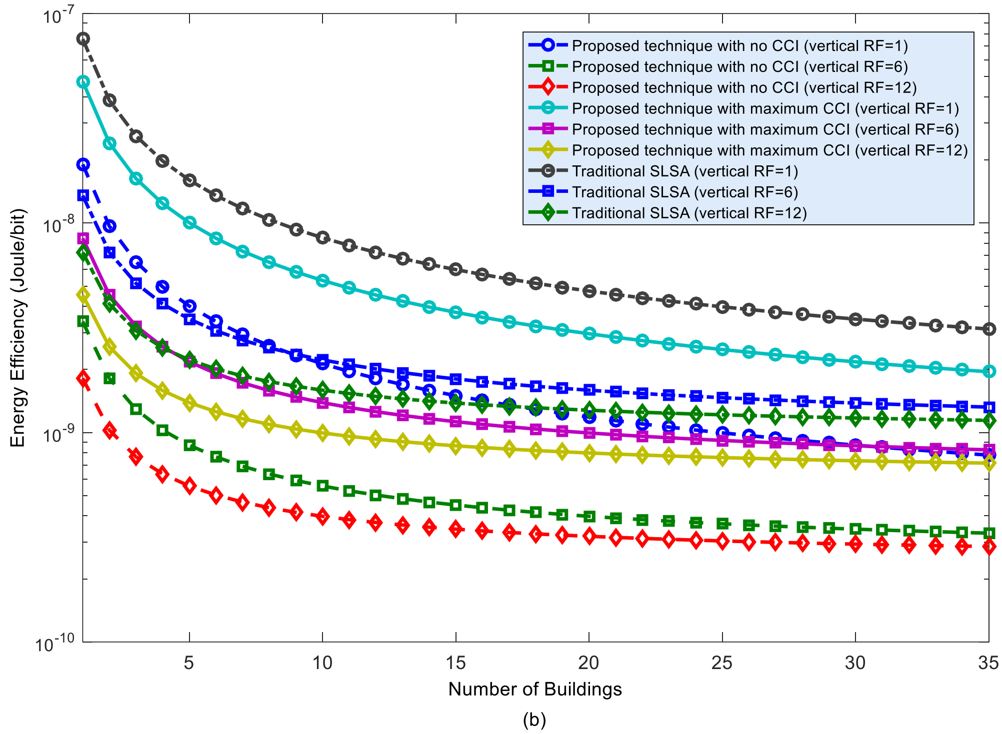


Figure 5. (a) SE and (b) EE performances of CoMSAR versus SLSA with a change in vertical RF and horizontal RF for MNO 1.

TABLE II. REQUIRED VERTICAL RF AND HORIZONTAL RF FOR THE PROPOSED AND SLSA TECHNIQUES TO SATISFY SE AND EE REQUIREMENTS FOR 6G MOBILE SYSTEMS.

Vertical RF	**Horizontal RF**								
	Proposed technique with no CCI		Proposed technique with maximum CCI		Traditional SLSA		Proposed technique with no CCI	Proposed technique with maximum CCI	Traditional SLSA
	SE	EE	SE	EE	SE	EE	Minimum required to satisfy SE and EE		
1	12	1	29	1	31	1	12	29	31
6	2	1	5	1	6	1	2	5	6
12	1	1	3	1	3	1	1	3	3

B. Further Outlooks

1) Implementation perspectives: The implementation of the proposed technique warrants the following issues [22], including updating the dynamic usage of the countrywide spectrum on each floor by UEs of different MNOs and enforcing CCI management. In this regard, SBSs of each MNO per floor can keep sensing using either a reactive or proactive approach to detect the status of the shared full countrywide spectrum usage and coordinate with SBSs of other MNOs on the same floor to update the CCI status and amount of the shared spectrum usage for each MNO. However, such coordination among SBSs of different MNOs generates a huge amount of control signaling overheads depending on the size of the group of the coordinated SBSs. The larger the size of the group of the coordinated SBSs, the greater the amount of generated control signaling overheads, as well as the delay in updating the CCI status.

In general, coordination among SBSs can be done centrally or in a distributed manner [22]. Central coordination of SBSs per building, for example, can contribute to achieving a global optimization in updating the CCI status and the corresponding spectrum allocation to each MNO. This, however, comes at the cost of generating high control signaling overheads. On the other hand, by limiting the size of a coordinated group of SBSs, control signaling overheads due to the coordination can be kept limited. This, however, comes at the cost of allowing a local optimization in updating the CCI status and the corresponding allocated spectrum to each MNO. Hence, a tradeoff between the optimal performance in the CCI and scheduled spectrum status updates per MNO and the generated control signaling overhead due to the coordination needs to be achieved, which asks for further studies [22]. We consider this issue as part of our future research studies.

2) Modeling 3D spectrum reuse: In this paper, we limit reusing the same countrywide full spectrum in small cells of an MNO *o* on each floor (i.e., 2-dimensional space) of a multistory building like [22]. However, the countrywide full spectrum allocated to an MNO o in the primary level can be exploited in the 3D space of a multistory building of small cells to increase the vertical RF even further for a building. More specifically, by enforcing a maximum CCI, a minimum distance between co-channel small cells (each located in an apartment) can be defined in both the intra-floor and inter-floor levels to form a 3D cluster of small cells of an MNO *o* within a building. The allocated spectrum per MNO can then be reused for each 3D cluster of small cells of an MNO *o* to improve the spectrum utilization. for example, adopting [13], a minimum distance between co-channel small cells for the 28 GHz mmWave spectrum in the intra-floor level and inter-floor level, respectively, for any MNO o at any term t_{rnw} can be expressed as follows [22].

$$\Delta_{\text{a}} = \Delta_{\text{m}} \times \left(\Xi_{\text{a}} \big/ I_{\text{a}}^{\text{thr}} \right)^{(1/1.797)} \tag{33}$$

$$\Delta_{\text{e}} \geq \Delta_{\text{m}} \times \left(\left(\Xi_{\text{e}} \big/ I_{\text{e}}^{\text{thr}} \right) \Big/ 10^{\left(\alpha_{\text{f}} (\Delta_{\text{e}})/10 \right)} \right)^{(1/1.797)} \tag{34}$$

where $I_{\text{a}}^{\text{thr}}$ and $I_{\text{e}}^{\text{thr}}$ denote, respectively, intra-floor and inter-floor CCI constraints at a small cell UE. Ξ_{a} and Ξ_{e} denote, respectively, the maximum number of co-channel small cells in the intra-floor level and inter-floor level. Δ_{m} denotes the minimum distance between a co-channel small cell and a small cell UE and $\alpha_{\text{f}}(\Delta_{\text{e}})$ denotes the floor penetration loss at 28 GHz.

Let s_l^{a} and s_l^{e} denote, respectively, the number of small cells corresponding to $\Delta_{\text{a},l}$ and $\Delta_{\text{e},l}$ in a building *l* such that a 3D cluster consists of $S_{\text{3D},l} = \left(s_l^{\text{a}} \times s_l^{\text{e}} \right)$ small cells. Hence, the same spectrum of MNO *o* can be reused for each cluster of $\left(s_l^{\text{a}} \times s_l^{\text{e}} \right)$ small cells in a building. Let $S_{\text{F},l}$ denote the maximum number of small cells of an MNO *o* in a building *l* such that the number of times the same spectrum of MNO *o* can be reused in building *l* (i.e., the spectrum RF for MNO *o* in building *l*) can be expressed as follows.

$$\omega_{\text{3D},l} = \frac{S_{\text{F},l}}{\left(s_l^{\text{a}} \times s_l^{\text{e}} \right)} \tag{35}$$

$$\omega_{\text{3D},l} = \frac{S_{\text{F},l}}{S_{\text{3D},l}} \tag{36}$$

Since the spectrum reuse can be performed to small cells deployed on the same floor of a building and the 28 GHz mmWave signal faces high floor penetration loss, $\omega_{\text{3D},l} \geq \omega_{\text{FL},l}$ may satisfy, resulting in improving the average capacity, SE, EE, and CE even further. Like [22], we consider this issue as w part of our future studies.

3) Impact of frequency bands on spectrum exploitation: The distance-dependent path loss varies with a change in carrier frequency. In general, an increase in carrier frequency causes to increase the path loss. Since the usable mmWave frequencies range largely, there is a corresponding impact on the reuse of the mmWave spectrum. For example, the distance-dependent path loss for the 60 GHz mmWave band can be expressed as [43] $PL(dB) = 68 + 21.7\log_{10}(d)$ where *d* is in the meter [22]. Like the 28 GHz band, adopting [13], a minimum distance between co-channel small cells for the path loss of 60 GHz mmWave spectrum as given above in the intra-floor level and inter-floor level, respectively, for any MNO o can be expressed as follows [22].

$$\Delta_{\text{a,60GHz}} = \Delta_{\text{m}} \times \left(\Xi_{\text{a}} \big/ I_{\text{a}}^{\text{thr}} \right)^{(1/2.17)} \tag{37}$$

$$\Delta_{\text{e,60GHz}} \geq \Delta_{\text{m}} \times \left(\left(\Xi_{\text{e}} \big/ I_{\text{e}}^{\text{thr}} \right) \Big/ 10^{\left(\alpha_{\text{f}} (\Delta_{\text{e,60GHz}})/10 \right)} \right)^{(1/2.17)} \tag{38}$$

where Δ_{m}, Ξ_{a} and $I_{\text{a}}^{\text{thr}}$ for the intra-floor level, as well as Ξ_{e} and $I_{\text{e}}^{\text{thr}}$ for the inter-floor level, are the same for both the 28-GHz and 60-GHz mmWave bands. Now, taking the ratio of (37) to (33), we can find the following for the intra-floor level.

$$\frac{\Delta_{\text{a,60GHz}}}{\Delta_{\text{a,28GHz}}} = \left(\Xi_{\text{a}} \big/ I_{\text{a}}^{\text{thr}} \right)^{(1/2.17)-(1/1.797)}$$

$$\frac{\Delta_{\text{a,60GHz}}}{\Delta_{\text{a,28GHz}}} = \left(\Xi_{\text{a}} \big/ I_{\text{a}}^{\text{thr}} \right)^{-0.373}$$

However, $0 \leq I_{\text{a}}^{\text{thr}} \leq 1$ and Ξ_{a} is a positive integer such that the following holds.

$$\left(\Xi_{\text{a}} \big/ I_{\text{a}}^{\text{thr}} \right)^{-0.373} < 1$$

Hence, $\Delta_{\text{a,60GHz}} < \Delta_{\text{a,28GHz}}$ (39)

This implies that the minimum distance in the intra-floor level decreases with an increase in frequency. Moreover, due to the higher frequency band, $\alpha_{\text{f}}\left(\Delta_{\text{e,60GHz}}\right) \geq \alpha_{\text{f}}\left(\Delta_{\text{e,28GHz}}\right)$. Hence, following the above procedure for the intra-floor level, it can be shown that the following holds for the inter-floor level.

$$\Delta_{\text{e,60GHz}} < \Delta_{\text{e,28GHz}} \tag{40}$$

Let $s_{l,\text{60GHz}}^{\text{a}}$ corresponds to $\Delta_{\text{a,60GHz}}$ and $s_{l,\text{60GHz}}^{\text{e}}$ corresponds to $\Delta_{\text{e,60GHz}}$ such that a 3D cluster at the 60 GHz band consists of $s_{\text{3D},l,\text{60GHz}} = \left(s_{l,\text{60GHz}}^{\text{a}} \times s_{l,\text{60GHz}}^{\text{e}} \right)$ small cells. Then, from (39) and (40), we can find the following.

$$\left(s^{\mathrm{a}}_{l,60\mathrm{GHz}} \times s^{\mathrm{e}}_{l,60\mathrm{GHz}}\right) < \left(s^{\mathrm{a}}_{l,28\mathrm{GHz}} \times s^{\mathrm{e}}_{l,28\mathrm{GHz}}\right)$$

$$s_{3\mathrm{D},l,60\mathrm{GHz}} < s_{3\mathrm{D},l,28\mathrm{GHz}} \tag{41}$$

Hence, the 3D cluster size decreases with an increase in frequency, i.e., more reuse of the same amount of spectrum bandwidth at the 60 GHz band can be made than that of the 28 GHz band for the same number of apartments in a building. Since there are other mmWave bands considered effective for the 5G and beyond mobile systems, including 26 GHz, 39 GHz, and 73 GHz, a detailed understanding of how the mmWave frequency bands impact their reuse in in-building scenarios is necessary [22], which we consider addressing as further studies.

4) MmWave spectrum allocation and reuse in outdoor environments: In this paper, we limit investigating the proposed countrywide mmWave spectrum allocation and reuse technique to indoor SBSs deployed in multistory buildings. However, the propagation characteristics of mmWave signals in outdoor environments differ greatly from those in indoor ones, particularly, rain and atmospheric absorption effect, cell coverage, shadowing effect from large buildings, outage probability, user density, and speed, and mobility and handover management. All these aspects have a significant impact on the allocation and reuse of the mmWave spectrum outdoors. Hence, how to allocate the countrywide mmWave spectrum to each MNO in outdoor environments without causing CCI to each other and reuse the same mmWave spectrum for any MNO spatially need considerable research work [22]. We aim to address this issue of the mmWave spectrum allocation and reuse in outdoor environments in our future research studies.

5) Effect of highly reflective environments: In general, the presence of LOS components is higher and the effect of multi-path fading from reflections, refractions, and scattering is less in high-frequency mmWave than in low-frequency microwave signals. So, even though, for simplicity, we consider no effect of highly reflective environments such as furniture and metal walls, ventilation installations, and elevator cars in the performance analysis of indoors in this paper, in practice, there may be some effects from such highly reflective environments in high-frequency signals. This requires further investigations, which we consider for our future studies.

VII. Conclusion

In this paper, we have proposed a countrywide millimeter-wave (mmWave) spectrum allocation and reuse (CoMSAR) technique that considers assigning each MNO with the 28 GHz mmWave spectrum countrywide at the cost of paying the spectrum licensing fee subject to avoiding co-channel interference (CCI). The assigned spectrum to each MNO is reused further to operate its small cells deployed on each floor in a multistory building. The amount of the spectrum licensing fee for an MNO is updated in accordance with its number of subscribers at each license renewal term. Moreover, CCI has been avoided by developing a frequency-domain CCI avoidance scheme that allocates UEs of different MNOs in an apartment on any floor of a building orthogonally to the countrywide 28 GHz mmWave spectrum. We have modeled user statistics per small cell and interferer statistics per apartment and formulated an expression for the optimal amount of spectrum of each MNO countrywide. By varying the impact of the CCI and the spectrum reuse, extensive numerical and simulation results and analyses have been carried out for an example scenario of a country consisting of four MNOs, i.e., MNO 1, MNO 2, MNO 3, and MNO 4 with a subscriber base of, respectively, 40%, 30%, 20%, and 10% of the total countrywide subscribers.

It has been shown that the proposed technique with no CCI provides 2.5 times higher average capacity, SE, EE, and CE performances than that with the maximum CCI. Furthermore, with regard to the SLSA, the proposed technique improves the average capacity, SE, EE, and CE of MNO 1 by 300%, 165%, 75%, and 60%, respectively, with no CCI. The improvement factors, however, decrease as CCI increases and reaches the minimum value when CCI is the maximum. Besides, the required SE and EE for 6G can be achieved by changing either vertical RF ω_{FL} or horizontal RF L such that their product, i.e., ($\omega_{\mathrm{FL}} \times L$), defines the achievable SE and EE performances. Further, the impact of CCI can be compensated by adjusting either vertical RF or horizontal RF. Furthermore, it has been shown that the proposed CoMSAR technique can satisfy both the SE of 370 bps/Hz and EE of 0.3 µJ/bit for 6G mobile systems by reusing the countrywide 28 GHz mmWave spectrum to small cells of MNO 1 of about 61.2% less number of single-floor buildings with no CCI, whereas 6.4% less number of single-floor buildings with the maximum CCI, than that required by the traditional SLSA technique. Lastly, we have discussed the benefits of the proposed technique and pointed out a number of issues as part of further studies on the proposed CoMSAR technique.

Appendix A

TABLE A1. LIST OF ACRONYMS/ABBREVIATIONS

Acronym/ Abbreviation	**Definition**
3D	3-Dimensional
6G	Sixth-Generation
BS	Base Station
CCI	Co-Channel Interference
CE	Cost Efficiency
CoMSAR	Countrywide Millimeter-wave Spectrum Allocation and Reuse
EE	Energy Efficiency
FFR	Fractional Frequency Reuse

ISD	Inter-Site Distance
LOS	Line-Of-Sight
mmWave	Millimeter-Wave
MNO	Mobile Network Operator
NLOS	Non-Line-Of-Sight
NRA	National Regulatory Agency
PBS	Picocell Base Station
RB	Resource Block
SBS	Small Cell Base Station
SE	Spectral Efficiency
SLSA	Static Licensed Spectrum Allocation
TTI	Transmission Time Interval
UE	User Equipment

TABLE A2. LIST OF SELECTED NOTATIONS

Notation	**Description**
t	Index of a TTI
T	Simulation run time with the maximum time of Q
O	Number of MNOs of a country
o	Index of an MNO
M	Amount of mmWave spectrum per MNO in SLSA
l	Index of a building
L	Number of buildings per macrocell
i	Index of an RB
P_{MC}, P_{PC}, and P_{SC}	The transmission power of a macrocell, a picocell, and a small cell, respectively, of an MNO o
ω_{FL}	Number of floors in a building
ω_{fl}	Index of a floor in a building
$M_{\mathrm{C,max}}$	Countrywide mmWave spectrum in RBs
t_{rnw}	Licensed renew term
$S_{\mathrm{F},o}$	Number of SBSs in any building l for an MNO o
ε_{C}	Cost of the countrywide 28 GHz mmWave spectrum $M_{\mathrm{C,max}}$
ε_{o}	Spectrum licensing fee paid by an MNO o
$N_{o,t_{\mathrm{rnw}}}$	Number of subscribers of an MNO o at term t_{rnw}
$N_{\mathrm{C,\,max},t_{\mathrm{rnw}}}$	Number of subscribers of a country at term t_{rnw}
$M_{o,t_{\mathrm{rnw},t}}^{l,\omega_{fl}}$	The optimal amount of licensed spectrum in RBs for an MNO o on any floor ω_{fl} in a building l in TTI t at term t_{rnw}
$\sigma_{t,i,o}^{t_{\mathrm{rnw}}}(\cdot)$	A link throughput at RB=i in TTI=t for an MNO o at t_{rnw} in bps per Hz
$\rho_{t,i,o}^{t_{\mathrm{rnw}}}(\cdot)$	A link SINR at RB=i in TTI=t for an MNO o at t_{rnw} in dB
$M_{\mathrm{MBS},o}$	Spectrum in RBs of a macrocell for an MNO o
$\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(\cdot)$, $\sigma_{\mathrm{FD,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(\cdot)$, $\sigma_{\mathrm{FD,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(\cdot)$, and $\varsigma_{\mathrm{FD,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}$	System-level average capacity, SE, EE, and CE, respectively, for all MNOs O countrywide at t_{rnw} for l=L when employing the proposed technique
$\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(\cdot)$, $\sigma_{\mathrm{SLSA,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(\cdot)$, $\sigma_{\mathrm{SLSA,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(\cdot)$, and $\varsigma_{\mathrm{SLSA,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}$	System-level average capacity, SE, EE, and CE, respectively, for all MNOs O countrywide at t_{rnw} for l=L when employing SLSA
$\varsigma_{\mathrm{cap},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$, $\varsigma_{\mathrm{SE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$, $\varsigma_{\mathrm{EE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$, and $\varsigma_{\mathrm{CE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$	Improvement factors in average capacity, SE, EE, and CE, respectively, due to applying the proposed technique

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