A Massive Millimeter-Wave Spectrum Allocation and Exploitation Technique Toward 6G Mobile Networks

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***Abstract*—In this paper, we propose a Countrywide Millimeter-Wave (mmWave) Spectrum Allocation and Reuse (CoMSAR) technique to allocate and reuse spatially the countrywide massive 28 GHz mmWave spectrum to each Mobile Network Operator (MNO) to operate its small cells per floor in a multistory building. A frequency-domain interference management scheme is developed, and the optimal amount of spectrum for each MNO is deduced to avoid Co-Channel Interference (CCI) at the presence of User Equipments (UEs) of multiple MNOs on each floor. We derive average capacity, Spectral Efficiency (SE), Energy Efficiency (EE), and Cost Efficiency (CE) for CoMSAR. Extensive numerical and simulation results and analyses are 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 is shown for MNO 1 that the proposed technique can improve average capacity, SE, EE, and CE by 300%, 165%, 75%, and 60%, respectively, with no CCI, whereas 60%, 6%, 37%, and 0.4%, respectively, with the maximum CCI. Further, we show that CoMSAR can satisfy the SE and EE requirements for sixth-generation (6G) mobile systems by reusing the countrywide 28 GHz mmWave spectrum to small cells of MNO 1 of about 60% less number of floors with no CCI, whereas 3.3% less number of floors with the maximum CCI, in a building.**

Keywords—6G; 28 GHz; countrywide; millimeter-wave; mobile network; spectrum allocation; spectrum exploitation; technique.

I. INTRODUCTION

The high capacity and data rates requirements for the existing mobile networks impose a demand for the massive radio spectrum availability on a Mobile Network Operator (MNO). 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. 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 as an effective approach to increase the utilization of the available spectrum.

Numerous research works have already addressed the issues of spectrum allocation [1]-[3], as well as spectrum exploitation [4]-[6]. For example, Yan et al. [1] have proposed methods for the dynamic spectrum allocation in cognitive radio systems. Kim et al. [2] have introduced the functionalities required for entities related to the spectrum allocation to propose a spectrum allocation algorithm in multiple network operators' scenario. Moreover, Kim et al. [3] have introduced and formulated the problem of the optimum spectrum allocation in cognitive radios. Besides, regarding the spectrum exploitation by means of reusing the available spectrum, Saha and Aswakul [4] have proposed an analytical model to reuse the spectrum in a 3D building of small cells. Likewise, Saquib et al. [5] have investigated a number of Fractional Frequency Reuse (FFR) schemes. Moreover, Saha [6] has proposed a technique to reuse the same spectrum by small cells deployed in a building by forming 3D clusters of small cells.

However, unlike the traditional static licensed spectrum allocation that considers allocating a certain portion of the countrywide spectrum to an MNO, the whole countrywide Millimeter-Wave (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 in the inter-floor level to reuse it 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 [7] 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 [8] 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 [9] 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. 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 derive average capacity, SE, EE, and CE metrics for the proposed technique. In Section IV, extensive numerical and simulation results and analyses for an example scenario of a country consisting of four MNOs is carried out under two extreme CCI scenarios, including no CCI and the maximum CCI, for an MNO to show that the proposed technique can achieve the SE and EE requirements for 6G mobile systems. We conclude the paper in Section V. A list of acronyms/abbreviations is shown in Table I and a list of selected notations is given in Table II.

II. SYSTEM ARCHITECTURE AND PROPOSED TECHNIQUE

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 each serving one User Equipment (UE) at a time (Figure 1(d)). 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, as shown in Figure 1(d). 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(d) shows two extreme CCI scenarios for small cells of MNO 1 on a floor based on the presence of UEs of other MNOs $\boldsymbol{O}\backslash o$ within the same floor of a building. For simplicity, CCI scenarios are shown for a single small cell 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 [10]-[12]. Hence, by exploiting the high floor penetration loss of 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(d)). 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 renew 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 (Figure 1(b)) due to the insignificant or no CCI generated between SBSs on adjacent floors. This results in reusing the allocated countrywide spectrum to an MNO more than once to its SBSs within a multistory building and, hence, in 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. Moreover, 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. *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 [13]. 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

TABLE I. 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
Non-LOS	NLOS
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 II. 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

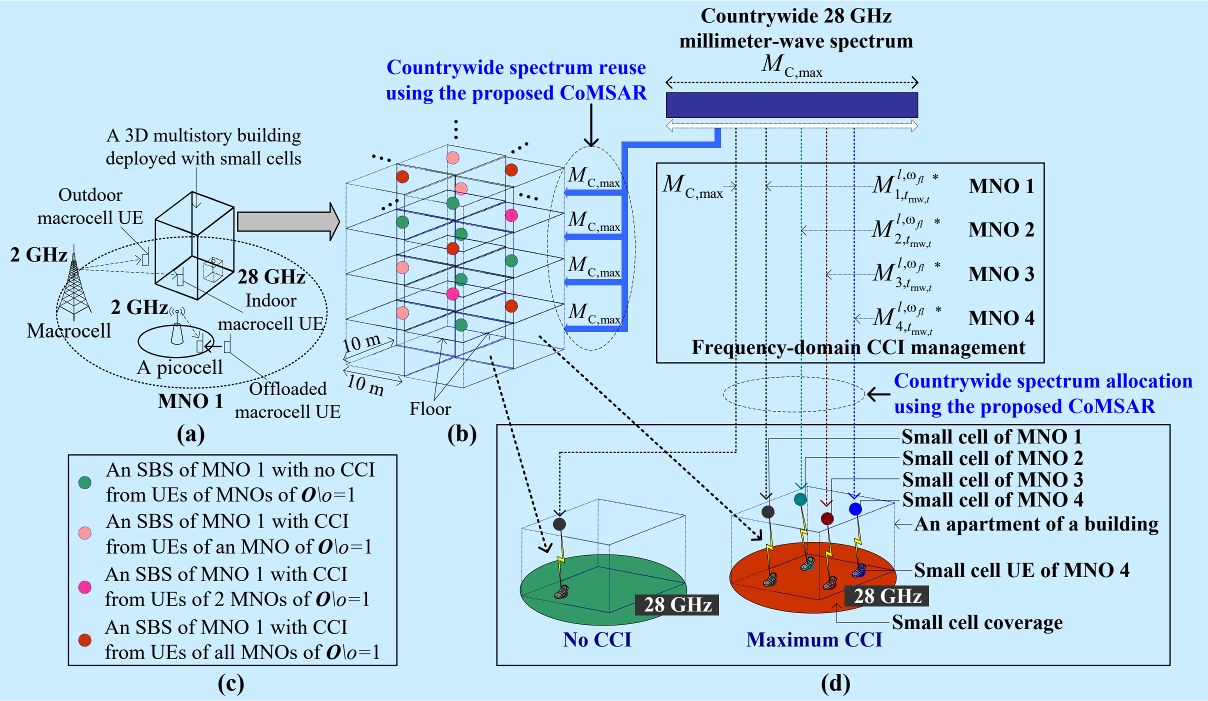

Figure 1. A system architecture consisting of four MNOs countrywide.

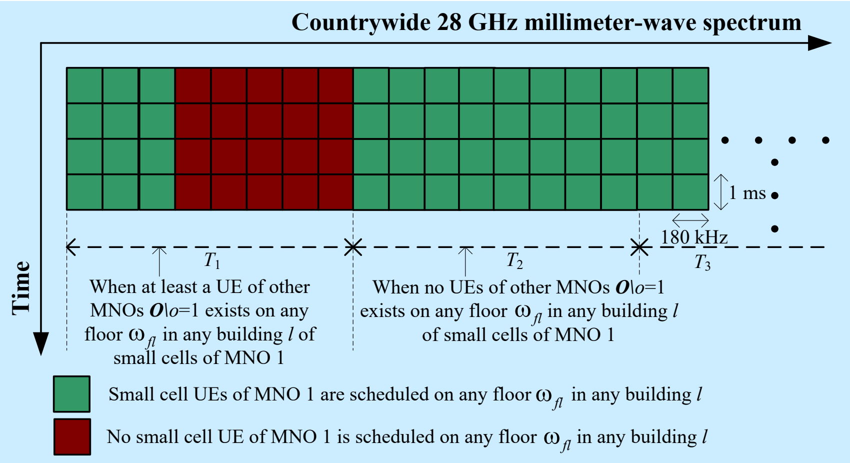

Figure 2. The frequency-domain CCI avoidance technique for UEs of MNO 1 on any floor ω_{fl} in a building l.
T_1, T_2, and T_3 define arbitrary and equal observation time intervals within $|\boldsymbol{T}| = Q$.

interfering UE can be detected either by the small cell or the small cell UE itself using any conventional spectrum sensing techniques.

D. 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 $s_{x,o} \in \boldsymbol{S_{x,o}} = \{0,1,2,...,S_{\mathrm{F},o}\}$ denote the number of small cells of an MNO o deployed on a number of floors $\omega_{fl} \in \boldsymbol{\omega}_{\mathrm{FL}} = \{1,2,...,\omega_{\mathrm{FL}}\}$ in any building $l \in \boldsymbol{L} = \{1,2,3,...,L\}$. Let $u_{x,o} \in \boldsymbol{U_{x,o}} = \{0,1,2,3,...,U_{\mathrm{F},o}\}$ denote the number of UEs of an MNO o corresponding to $s_{x,o} \in \boldsymbol{S_{x,o}}$ in any $l \in \boldsymbol{L}$. Denote $M_{\mathrm{C,max}}$ as the countrywide total amount of mmWave spectrum defined in terms of the number of Resource Blocks (RBs) where a RB is equal to 180 kHz.

Let $N_{o,t_{\mathrm{mw}}}$ denote the total number of subscribers of an MNO o such that $\sum_{o}^{O} N_{o,t_{\mathrm{mw}}} \le N_{\mathrm{C,\,max},t_{\mathrm{mw}}}$ where $N_{\mathrm{C,\,max},t_{\mathrm{mw}}}$ denotes the maximum number of subscribers of a country at term t_{mw}. Assume that each small cell $s_{x,o}$ of an MNO o can serve the maximum of one UE $u_{x,o}$ at a time. 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 $u_{x,o}$ 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 $u_{x,o}$ 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 $N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}}$ of the MNO o to the sum of the total number of subscribers $N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t}$ of all MNOs O=4 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 to 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 $M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}$ 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.

$$\begin{aligned} &\min_{o\in\boldsymbol{O}} && M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}} \\ &\text{subject to} && \text{(a) } N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}} \Big/ N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t} = M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}} \Big/ M_{\mathrm{C,max}} \qquad (1) \\ & && \text{(b) } \forall o \forall t_{\mathrm{rnw}} \forall l \forall \omega_{fl} \textstyle\sum_{o}^{O} N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}} N_{o,t_{\mathrm{rnw}}} \le N^{l,\omega_{fl}}_{\mathrm{C,\,max},t_{\mathrm{rnw}}} \end{aligned}$$

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

$$M^{l,\omega_{fl}\;*}_{o,t_{\mathrm{rnw},t}} = \left\lceil \left(\left(N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}} \Big/ \sum_{o=1}^{O} \left(1_{\nu_o}\left(N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}} \right) \times N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}} \right) \right) \times M_{\mathrm{C,max}} \right) \right\rceil \qquad (2)$$

Proof 1: The solution to the optimization problem in (1) 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 $N_{1,t_{\mathrm{rnw}}} > N_{2,t_{\mathrm{rnw}}} > \ldots > N_{O,t_{\mathrm{rnw}}}$ at t_{rnw} such that the constraint 1(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

$$N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t} = \sum_{o=1}^{O} \left(1_{\nu_o}\left(N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}} \right) \times N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}} \right) \qquad (3)$$

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

Since the number of RBs is strictly an integer, using (3), and the constraint 1(a), the optimal value of $M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}$ is given by

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

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

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 $N^{l,\omega_{fl}}_{t_{\mathrm{rnw}},t} = N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}}$ in (3), 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 $u_{x,o} \in \boldsymbol{U_{x,o}}$ of small cells $s_{x,o} \in \boldsymbol{S_{x,o}}$ 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. Hence, using (2), 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 $N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}}$ 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 $N^{l,\omega_{fl}}_{o,t_{\mathrm{rnw}}}$ of an MNO o on any floor ω_{fl} in a building l in any TTI t at term t_{rnw}, the greater the amount of mmWave spectrum $M^{l,\omega_{fl}}_{o,t_{\mathrm{rnw},t}}$ allocated to MNO o corresponding to the same floor in the building l in TTI t at term t_{rnw}.

III. MATHEMATICAL ANALYSIS

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 step 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 [14][15]

$$\sigma^{t_{\mathrm{rnw}}}_{t,i,o}\left(\rho^{t_{\mathrm{rnw}}}_{t,i,o}\right) = \left\{ \begin{array}{ll} 0, & \rho^{t_{\mathrm{rnw}}}_{t,i,o} < -10\,\mathrm{dB} \\ \beta \log_2\left(1 + 10^{\left(\rho^{t_{\mathrm{rnw}}}_{t,i,o}(\mathrm{dB})/10\right)}\right), & -10\,\mathrm{dB} \le \rho^{t_{\mathrm{rnw}}}_{t,i,o} \le 22\,\mathrm{dB} \\ 4.4, & \rho^{t_{\mathrm{rnw}}}_{t,i,o} > 22\,\mathrm{dB} \end{array} \right\} \qquad (4)$$

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

$$\sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}} = \sum\nolimits_{t=1}^{Q} \sum\nolimits_{i=1}^{M_{\mathrm{MBS},o}} \sigma_{t,i,o}^{t_{\mathrm{rnw}}} \left(\rho_{t,i,o}^{t_{\mathrm{rnw}}} \right) \tag{5}$$

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 in a building l, of an MNO o at a renewal term t_{rnw} are given respectively by

$$\sigma_{\mathrm{FD},o,l,s_{x,o}}^{t_{\mathrm{rnw}},\omega_{fl}} = \sum_{t \in \boldsymbol{T}} \sum\nolimits_{i=1}^{M_{o,t_{\mathrm{rnw}},t}^{l,\omega_{fl}\ *}} \sigma_{t,i,o}^{t_{\mathrm{rnw}}} \left(\rho_{t,i,o}^{t_{\mathrm{rnw}}} \right) \tag{6}$$

$$\sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{fl}} = \sum\nolimits_{s_{x,o}=1}^{S_{\omega_{fl},o}} \sigma_{\mathrm{FD},o,l,s_{x,o}}^{t_{\mathrm{rnw}},\omega_{fl}} \tag{7}$$

$$\sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}} = \sum\nolimits_{\omega_{fl}=1}^{\omega_{\mathrm{FL}}} \sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{fl}} \tag{8}$$

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

$$\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sum\nolimits_{o=1}^{O} \left(\sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}} + \left(L \times \sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}} \right) \right) \tag{9}$$

Since $\left(L \times \sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}} \right) >> \sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}}$, roughly, (9) can be given by

$$\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \cong \sum\nolimits_{o=1}^{O} \left(L \times \sigma_{\mathrm{FD},o,l,s_{\omega_{fl},o}}^{t_{\mathrm{rnw}},\omega_{\mathrm{FL}}} \right) \tag{10}$$

$$\sigma_{\mathrm{FD,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \Big/ \left(\left(M_{\mathrm{C,max}} + \sum\nolimits_{o=1}^{O} M_{\mathrm{MBS},o} \right) \times Q \right) \tag{11}$$

$$\sigma_{\mathrm{FD,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \left(\sum\nolimits_{o=1}^{O} \left(\begin{array}{l} \left(L \times S_{\mathrm{F},o} \times P_{\mathrm{SC}} \right) \\ + \left(S_{\mathrm{P},o} \times P_{\mathrm{PC}} \right) + \left(S_{\mathrm{M},o} \times P_{\mathrm{MC}} \right) \end{array} \right) \right) \Bigg/ \left(\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) / Q \right) \tag{12}$$

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

However, in a traditional Static Licensed Spectrum Allocation (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 (8)-(12), the system-level average capacity, SE, and EE for all MNOs O countrywide at t_{rnw} for l=L can be given by

$$\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sum\nolimits_{o=1}^{O} \left(\sigma_{\mathrm{MBS},o}^{t_{\mathrm{rnw}}} + \left(L \times \sum\nolimits_{\omega_{fl}=1}^{\omega_{\mathrm{FL}}} \sum\nolimits_{s_{x,o}=1}^{S_{\omega_{fl},o}} \sum_{t \in \boldsymbol{T}} \sum\nolimits_{i=1}^{M} \sigma_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}} \left(\rho_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}} \right) \right) \right) \tag{13}$$

$$\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \cong \sum\nolimits_{o=1}^{O} \left(L \times \sum\nolimits_{\omega_{fl}=1}^{\omega_{\mathrm{FL}}} \sum\nolimits_{s_{x,o}=1}^{S_{\omega_{fl},o}} \sum_{t \in \boldsymbol{T}} \sum\nolimits_{i=1}^{M} \sigma_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}} \left(\rho_{s_{x,o},t,i,o}^{t_{\mathrm{rnw}},\omega_{fl}} \right) \right) \tag{14}$$

$$\sigma_{\mathrm{SLSA,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \Big/ \left(\left(M_{\mathrm{C,max}} + \sum\nolimits_{o=1}^{O} M_{\mathrm{MBS},o} \right) \times Q \right) \tag{15}$$

$$\sigma_{\mathrm{SLSA,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) = \left(\sum\nolimits_{o=1}^{O} \left(\begin{array}{l} \left(L \times S_{\mathrm{F},o} \times P_{\mathrm{SC}} \right) + \\ \left(S_{\mathrm{P},o} \times P_{\mathrm{PC}} \right) + \left(S_{\mathrm{M},o} \times P_{\mathrm{MC}} \right) \end{array} \right) \right) \Bigg/ \left(\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) / Q \right) \tag{16}$$

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

$$\varepsilon_o = \left(N_{o,t_{\mathrm{rnw}}} / N_{\mathrm{C,\,max},t_{\mathrm{rnw}}} \right) \times \varepsilon_{\mathrm{C}} \tag{17}$$

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.

$$\varsigma_{\mathrm{FD,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} = \varepsilon_{\mathrm{C}} \Big/ \sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \tag{18}$$

$$\varsigma_{\mathrm{SLSA,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} = \varepsilon_{\mathrm{C}} \Big/ \sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \tag{19}$$

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.

$$\varsigma_{\mathrm{cap},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \Big/ \sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \tag{20}$$

$$\varsigma_{\mathrm{SE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \sigma_{\mathrm{FD,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \Big/ \sigma_{\mathrm{SLSA,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \tag{21}$$

$$\varsigma_{\mathrm{EE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \sigma_{\mathrm{FD,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \Big/ \sigma_{\mathrm{SLSA,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L) \tag{22}$$

$$\varsigma_{\mathrm{CE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}} = \varsigma_{\mathrm{FD,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} \Big/ \varsigma_{\mathrm{SLSA,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}} \tag{23}$$

IV. PERFORMANCE EVALUATION

A. *Performance Result and Analysis*

Table III shows the default simulation parameters and assumptions used for evaluating the performances of the proposed technique. We generate performance results by simulating all assumptions and parameters given in Table III by a simulator that is built by using the default instruction sets of the computational tool MATLAB R2012b version running on a personal computer. Further, the algorithm used to generate the performance results is given in Algorithm 1. 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 $N_{\mathrm{C},\max,t_{\mathrm{rnw}}}$ at any term t_{rnw} (Table III). Using (20)-(23), the performance of the proposed technique is evaluated for MNO 1 under 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 at least a UE of each MNO of $\boldsymbol{O}\backslash o=1$ on a floor in a building. With no CCI, the whole countrywide mmWave spectrum, whereas with the maximum CCI, only 40% of the countrywide spectrum, can be allocated to SBSs of MNO 1 in all TTIs. Since the achievable capacity depends directly on the amount of spectrum, the maximum average capacity, SE, EE, and CE for MNO 1 can be achieved with no CCI, as shown in Figure 3(a), in contrast to that with the maximum CCI, shown in Figure 3(b). Specifically, with regard to the traditional SLSA, the proposed technique improves the average capacity, SE, EE, and CE by 300%, 165%, 75%, and 60%, respectively with no CCI, whereas only 60%, 6%, 37%, and 0.4%, respectively with the maximum CCI.

TABLE III. DEFAULT PARAMETERS AND ASSUMPTIONS

Parameters and Assumptions	**Value**
28 GHz spectrum countrywide	200 MHz
Number of MNOs and subscribers	4 and $N_{\mathrm{C,max}}$
Number of subscribers for MNOs 1, 2, 3, and 4, respectively	40%, 30%, 20%, and 10% of $N_{\mathrm{C,max}}$
For each MNO	
E-UTRA simulation case[1,6]	3GPP case 3
Cellular layout[2,6], Inter-Site Distance (ISD)[1,2,6], transmit direction	Hexagonal grid, dense urban, 3 sectors per macrocell site, 1732 m, downlink
Carrier frequency[2,5,6]	2 GHz Non-line-of-Sight (NLOS) for macrocells and picocells, 28 GHz Line-of-Sight (LOS) for all small cells
Number of cells	1 macrocell, 2 picocells, 280 small cells per building
Total BS transmit power[1] (dBm)	46 for macrocell[1,4], 37 for picocells[1], 19 for small cells[1,3,4]
Co-channel small-scale fading model[1,3,5]	Frequency selective Rayleigh for 2 GHz, none for 28 GHz
Path loss — MBS and a UE[1] — Outdoor macrocell UE	$PL(\mathrm{dB})=15.3+37.6\log_{10}R$, R is in m
Path loss — MBS and a UE[1] — Indoor macrocell UE	$PL(\mathrm{dB})=15.3+37.6\log_{10}R+L_{\mathrm{ow}}$, R is in m
Path loss — PBS and a UE[1]	$PL(\mathrm{dB})=140.7+36.7\log_{10}R$, R is in km
Path loss — SBS and a UE[1,2,5]	$PL(\mathrm{dB})=61.38+17.97\log_{10}(d)$, d is in m
Lognormal shadowing standard deviation (dB)	8 for MBS[2], 10 for PBS[1], and 9.9 for SBS[2,5]
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]	0 dBi (for 2 GHz), 5 dBi (for 28 GHz, Biconical horn)
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, number of macrocell UEs, and macrocell UEs offloaded to all picocells[1]	40 m (radius), 30, 2/15
Indoor macrocell UEs[1]	35%
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, number of SBSs per building, area of an apartment, materials used	*L,* 35, 8, 1, 280, 10×10 m^2, reinforced concrete
Scheduler and traffic model[2]	Proportional Fair and full buffer
Type of SBSs	Closed Subscriber Group femtocell BSs
Channel State Information	Ideal
TTI[1] and scheduler time constant (t_{c})	1 ms and 100 ms
Total simulation run time	8 ms

taken [1]from [16], [2]from [17], [3]from [18], [4]from [19], from [5][20], from [6][21].

Algorithm 1. Proposed CoMSAR technique

```
Input: $O=4$, $Q$, $t_{\mathrm{rnw}}$, $N_{\mathrm{C},\max,t_{\mathrm{rnw}}}$ $M$, $N_{o,t_{\mathrm{rnw}}}$, $M_{\mathrm{C,max}}$
        $s_{x,o}\in\boldsymbol{S}_{\boldsymbol{x,o}}=\{0,1,2,\dots,S_{\mathrm{F},o}\}$, $P_{\mathrm{MC}}$, $P_{\mathrm{PC}}$, $P_{\mathrm{SC}}$
  For $L=\{1,2,3,\dots,\}$
    For $t=\{1, 2, 3,\dots,Q\}$
      For $o\in\boldsymbol{O}=\{1,2,\dots,O\}$
        Find $M_{o,t_{\mathrm{rnw},t}}^{l,\omega_{fl}}{}^{*}$ using (2)
        Estimate Capacity, $\sigma_{\mathrm{FD,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$ using (9)
                 and $\sigma_{\mathrm{SLSA,cap},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$ using (14)
        Estimate SE $\sigma_{\mathrm{FD,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$ using (11)
                 and $\sigma_{\mathrm{SLSA,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$ using (15)
        Estimate EE $\sigma_{\mathrm{FD,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$ using (12)
                 and $\sigma_{\mathrm{SLSA,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$ using (16)
        Estimate CE $\varsigma_{\mathrm{FD,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}$ using (18)
                 and $\varsigma_{\mathrm{SLSA,CE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}$ using (19)
      End
    End
  End
  Find Improvement factors using (20)-(23):
        $\varsigma_{\mathrm{cap},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$, $\varsigma_{\mathrm{SE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$, $\varsigma_{\mathrm{EE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$, $\varsigma_{\mathrm{CE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$
Output: Display for MNO $o=1$ the followings:
        $\varsigma_{\mathrm{cap},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$ $\varsigma_{\mathrm{SE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$ $\varsigma_{\mathrm{EE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$, $\varsigma_{\mathrm{CE},O,\mathrm{IF}}^{\mathrm{sys},t_{\mathrm{rnw}}}$
Plot: For no and maximum CCI for MNO $o=1$:
  $\sigma_{\mathrm{FD,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$, $\sigma_{\mathrm{SLSA,SE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$, $\sigma_{\mathrm{FD,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$, $\sigma_{\mathrm{SLSA,EE},O}^{\mathrm{sys},t_{\mathrm{rnw}}}(L)$
```

Moreover, Figure 3 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. Hence, CCI plays a vital role in the overall performances of an MNO

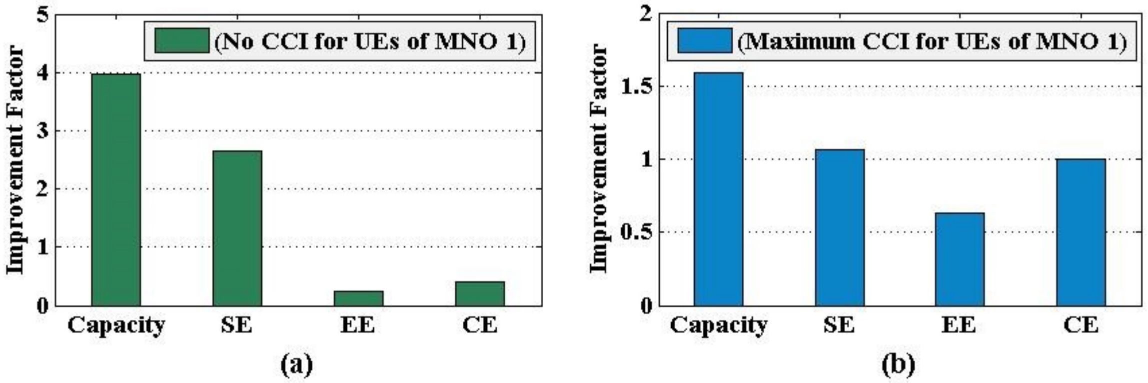

Figure 3. Performance improvement of the proposed CoMSAR technique for MNO 1 in terms of average capacity, SE, EE, and CE (a) with no CCI and (b) with the maximum CCI for UEs of MNO 1 on a single floor in a building.

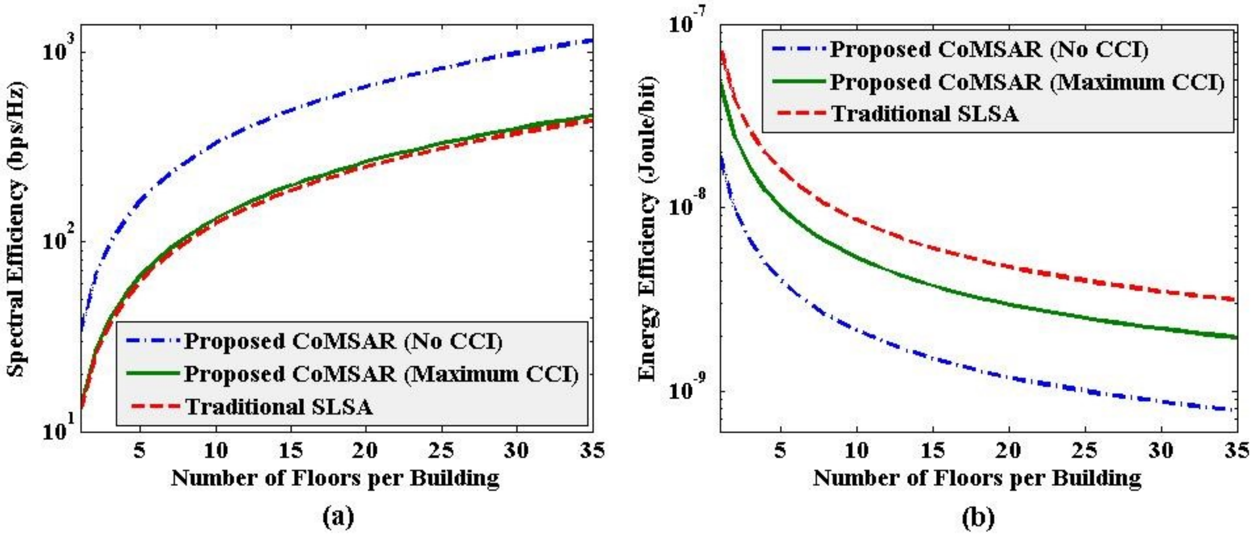

Figure 4. (a) SE and (b) EE performances of CoMSAR with respect to SLSA for a multistory building with $\omega_{FL} = 35$.

when allocated to the countrywide spectrum. Now, using (10) -(12) for the proposed technique and (14) -(16) for the traditional SLSA technique, Figures 4(a) and 4(b) show the effect of reusing the same countrywide spectrum to each floor of SBSs of MNO 1 in a multistory building. As can be seen from Figure 4, with an increase in the number of floors, SE increases linearly, whereas EE increases negative exponentially, irrespective of the degree of CCI. Further, 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 Figure 3(b).

B. Performance Comparison

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) [22] [23], of 5G mobile systems [24] [25]. Now, using Figure 4, it can be seen that the proposed CoMSAR 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 60% less number of floors (i.e., ω_{FL} =12) with no CCI, whereas 3.3% less number of floors (i.e., ω_{FL} =29) with the maximum CCI, than that required by the traditional SLSA technique (i.e., ω_{FL} =30) in a multistory building.

C. Offered Benefits and Implementation Complexity

The proposed technique benefits from the following. It 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. 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).

However, the implementation of the proposed technique warrants from the following issues, 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 delay in updating the CCI status.

In general, coordination among SBSs can be done centrally or in a distributed manner. 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. We consider this issue as part of our future research studies.

V. 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 massive 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 renew term. Moreover, CCI has been avoided by developing a frequency-domain CCI avoidance scheme that allocates UEs of different MNOs on any floor of a building orthogonally to the countrywide 28 GHz mmWave spectrum. We have derived average capacity, Spectral Efficiency (SE), Energy Efficiency (EE), and Cost Efficiency (CE) metrics for the proposed technique. 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 the number of subscribers of 40%, 30%, 20%, and 10% of the total number of subscribers of all MNOs, respectively.

It has been shown for MNO 1 that, for a single building of small cells, the proposed technique can improve the average capacity, SE, EE, and CE performances by 300%, 165%, 75%, and 60%, respectively with no CCI, whereas 60%, 6%, 37%, and 0.4%, respectively with the maximum CCI, as compared to that of the traditional Static Licensed Spectrum Allocation (SLSA) technique. Finally, we have shown that the proposed CoMSAR technique can satisfy the SE and EE requirements for 6G mobile systems by reusing the countrywide 28 GHz mmWave spectrum to small cells of MNO 1 of about 60% less number of floors with no CCI, whereas 3.3% less number of floors with the maximum CCI, than that required by the traditional SLSA technique in a multistory building.

So far, in this paper, we have restricted 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 that in indoor one, 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 without causing CCI to each other and reuse the same mmWave spectrum for an MNO spatially need considerable research works. We aim to address these issues, i.e., mmWave spectrum allocation and reuse, in outdoor environments in our future research studies.

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