Approaches to Improve Millimeter-Wave Spectrum Utilization Using Indoor Small Cells in Multi-Operator Environments Toward 6G

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ABSTRACT In this paper, we propose two spectrum utilization improvement approaches (SUIAs), namely SUIA 1 and SUIA 2, based on whether or not the licensed 28 GHz millimeter-wave (mmWave) spectrum is allocated equally to each mobile network operator (MNO) in a country. Principally, SUIA 1 concerns with improving spectrum utilization if the 28 GHz spectrum is allocated equally to each MNO statically, also termed as static licensed spectrum allocation (SLSA). Whereas, SUIA 2 concerns with improving spectrum utilization if the spectrum is allocated unequally to each MNO in a flexible manner, also termed as flexible licensed spectrum allocation (FLSA). Since sharing and reusing of the licensed spectrum allocated to each MNO using either SLSA or FLSA can be exploited, and the secondary spectrum trading is required only in case of SLSA to redistribute the assigned spectra among MNOs. SUIA 1 employs SLSA, spectrum trading, spectrum sharing, and spectrum reusing techniques, whereas SUIA 2 employs FLSA, spectrum sharing, and spectrum reusing techniques. We present mathematical models for each technique and derive average capacity, spectral efficiency (SE), and energy efficiency (EE) metrics for SUIA 1 and SUIA 2. Extensive numerical and simulation results and analyses for SUIA 1 and SUIA 2 are carried out. It is shown that the spectrum reusing technique influences mostly SE and EE performances. Moreover, SE and EE performances of an MNO in SUIA 1 do not differ considerably from that in SUIA 2 such that depending on the spectrum allocation policies and practices in a country, either SUIA 1 or SUIA 2 can be employed. Finally, it is shown that by applying both SUIA 1 and SUIA 2, the prospective average SE and average EE requirements for sixth-generation (6G) mobile networks can be satisfied.

INDEX TERMS 28 GHz, 5G, 6G, millimeter-wave, approach, mobile network operator, small cells, spectrum allocation, spectrum sharing, spectrum trading, spectrum reusing, spectrum utilization.

I. INTRODUCTION

A. BACKGROUND

The demands for the high data rate and network capacity of a mobile network operator (MNO) have been ever-increasing. However, the available spectrum for an MNO has not been increased accordingly. Further, an MNO needs to provide high quality-of-service (QoS) at a low cost per bit transmission, but at a high cost of licensing its operating spectrum. All these cause an MNO in a country to realize new approaches to addressing the high cost and scarcity of the radio spectrum while serving the growing user demand over time at a low cost per bit and high QoS. In this regard, improving the utilization of the available radio spectrum of an MNO is considered an effective approach, and one of the major concerns in mobile wireless communications [1]–[5].

Efficient spectrum utilization can be achieved in several ways [4]. In this regard, spectrum allocation, spectrum sharing, spectrum trading, and spectrum reusing techniques have been found promising and play a significant role in enhancing the utilization of the spectrum of an MNO in a country. More specifically, the licensed spectrum is traditionally allocated to an MNO in a static manner for a long time. However, such static allocation may cause inefficient utilization of the licensed spectrum for an MNO. This can be overcome by allocating the licensed spectrum to an MNO flexibly in accordance with its actual demand, e.g. its subscriber-base. Further, the spectrum utilization can be improved either by...
sharing dynamically the licensed spectrum of one MNO with another, or by taking a lease of a portion of the licensed spectrum of one MNO by another under secondary spectrum trading, or by reusing the same licensed spectrum of an MNO spatially subject to avoiding co-channel interference.

Besides, most mobile data is generated in indoor environments, particularly within multistory buildings in urban environments. Accordingly, due to the availability of a large amount of spectrum bandwidth, as well as the favorable signal propagation characteristics for short-distance communications using small cells in indoor environments, millimeter-wave (mmWave) spectrum bands are considered as promising candidate bands to address the high data rate and capacity demands of next-generation mobile systems such as fifth-generation (5G) and beyond systems. In this regard, the 28 GHz band is considered as one of the promising mmWave bands. Hence, studies on developing approaches for allocation, sharing, trading, and reusing the licensed 28 GHz mmWave spectrum using in-building small cells to improve the utilization of the 28 GHz mmWave spectrum to address high data rates and capacity of next-generation mobile systems are considered crucial.

B. RELATED WORK

To clarify further, spectrum allocation techniques define how the spectrum specified for a country is allocated to its MNOs by either the national regulatory agency or any third party. Each MNO can serve its users only using its allocated spectrum on an exclusive basis. The efficacy of a spectrum allocation technique is considerably affected by factors, such as the amount and duration of the allocated spectrum to an MNO and the user traffic demand of an MNO.

Since the user traffic demand of an MNO varies in time and space, the whole allocated spectrum to each MNO may not be used at the same time and place. Due to this reason, the allocated spectrum to an MNO can be shared opportunistically with other MNOs in a country subject to satisfying a certain co-channel interference threshold. Such a technique is termed as dynamic spectrum sharing to address the scarcity of spectrum of an MNO, and hence to improve the countrywide spectrum utilization. Cognitive radio technology is considered as an effective means to address the dynamic spectrum sharing between MNOs.

However, unlike the primary-level dynamic spectrum sharing as aforementioned, the scarcity of available spectrum of an MNO can also be addressed by exploiting the secondary spectrum trading technique such that an MNO with the scarcity of spectrum can take a lease from another MNO with unused spectrum at the cost of payment for the corresponding leased spectrum for a certain term. Such a technique to redistribute the allocated spectra between MNOs is termed as spectrum trading that results in improving the overall countrywide spectrum utilization.

Furthermore, due to the distant-dependent path loss, the utilization of the spectrum allocated to an MNO can also be improved by reusing its spectrum in space subject to satisfying a certain co-channel interference threshold between its co-channel base stations. Since higher frequencies are attenuated more, the spectrum reuse in space and hence the allocated spectrum utilization of an MNO increase with an increase in its carrier frequency. Therefore, unlike spectrum sharing and spectrum trading techniques, the spectrum reusing technique does not need any interaction with other MNOs in a country.

Numerous studies in existing literature have addressed the issues of spectrum allocation, sharing, trading, and reusing. For example, regarding spectrum allocation, in [6], the authors presented a system-level dynamic frequency spectrum allocation scheme based on central heterogeneous network architecture. The authors of [7] considered resource allocation optimization problem with carrier aggregation. Further, the authors of [8] proposed a joint subcarrier and power allocation method based on the access mechanism. Furthermore, in [9], the authors developed a traffic-load aware channel allocation mechanism for secondary users with respect to their applications' QoS requirements. Besides, the authors of [10] proposed a new dynamic spectrum allocation algorithm to resolve channel conflict problems in channel switching in the vehicle network.

For spectrum sharing, the authors studied the main concepts of dynamic spectrum sharing and different sharing scenarios in [11]. In [12], the authors studied spectrum sharing approaches, as well as user association mechanisms, in mmWave systems. Further, the authors of [11] studied co-primary shared access methods, namely spectrum pooling and mutual renting. Furthermore, the authors of [13] presented inter-operator dynamic spectrum access algorithms based on the game theory, and the authors of [14] addressed the spectrum sharing problem between two operators in a dynamic network. Besides, in [15], the authors introduced a new hybrid spectrum access scheme for mmWave networks where data packets are scheduled through two mmWave carriers with different characteristics.

For spectrum trading, the authors of [16] considered multiple sellers and multiple buyers such that sellers compete to set the spectrum price, and buyers select the spectrum depending on either the quality or the price of sellers. The authors of [17] proposed a matching based double auction mechanism for spectrum trading with differential privacy to protect the privacy of buyers/sellers. In [18], the authors proposed a scheme using the evolutionary game theory for selling the spectra of multiple primary users to multiple secondary users. Further, in [19], the authors introduced a bandwidth-auction game for the spectrum trading problem of a cellular network consisting of multiple cellular user equipments (UEs) and a cognitive device-to-device pair. Furthermore, in [20], the authors studied the spectrum trading system from the service-oriented perspective considering all three aspects of secondary spectrum licensees, spectrum market, and primary spectrum licensees.

Finally, for spectrum reusing, in [21], the authors investigated three fractional frequency reuse (FFR) schemes,
including strict FFR, soft FFR, and FFR-3. The authors of [22] developed new FFR patterns for multi-cell orthogonal frequency-division multiple access systems with frequency or time division duplexing (FDD/TDD) in time-varying channels. The authors of [23] proposed a dynamic fractional frequency reuse (DFFR) method for reducing the inter-cell interference automatically. In [24], the authors presented a comparison of the performance of well-known frequency reuse algorithms in terms of system throughput, average packet loss ratio, and average packet delay. In [25], the authors proposed an analytical approach to reuse the same spectrum multiple times to femtocells deployed a building.

Hence, based on the above discussion, spectrum allocation, spectrum sharing, spectrum trading, and spectrum reusing techniques have been studied discretely in the existing literature, resulting in improving spectrum utilization moderately. However, integrating all these techniques together, particularly for the licensed 28 GHz mmWave spectrum of any MNO in a country using in-building small cells, can contribute to improving the utilization of the 28 GHz mmWave spectrum considerably, which is not obvious in the existing literature. We address this issue in this paper.

C. CONTRIBUTION
In this paper, unlike the existing literature where spectrum allocation, spectrum sharing, spectrum trading, and spectrum reusing techniques have been investigated separately, we propose two spectrum utilization improvement approaches (SUIAs), namely SUIA 1 and SUIA 2 each of which integrates a number of these techniques, based on whether or not the licensed 28 GHz mmWave spectrum is allocated equally to each MNO in a country in the primary-level. Principally, SUIA 1 concerns with improving the 28 GHz mmWave spectrum utilization if the licensed 28 GHz mmWave spectrum is allocated equally to each MNO in a country in a static manner, which we term it as static licensed spectrum allocation (SLSA). Whereas, SUIA 2 concerns with improving the 28 GHz mmWave spectrum utilization if the mmWave spectrum is allocated unequally to each MNO flexibly, which we term it as flexible licensed spectrum allocation (FLSA). Since sharing and reusing of the licensed spectrum allocated to each MNO using either SLSA or FLSA can be exploited, and the secondary spectrum trading is required only in case of SLSA to redistribute the statically assigned licensed spectra among MNOs, SUIA 1 employs SLSA, spectrum trading, spectrum sharing, and spectrum reusing techniques, whereas SUIA 2 employs FLSA, spectrum sharing, and spectrum reusing techniques.

We describe the system architecture and the concept of all techniques for both approaches SUIA 1 and SUIA 2. With regard to spectrum sharing, we consider that a portion of the mmWave spectrum of each MNO in a country is made common in a pool such that the spectrum pool can be shared by small cells of each MNO simultaneously subject to avoiding co-channel interference caused by the other MNOs in the pool. About spectrum trading, an MNO can lease a part of its spectrum exclusively to other MNOs for a certain duration of time by exploiting the secondary spectrum trading. However, for spectrum reusing, we consider that the mmWave spectrum of an MNO can be reused fully to each 3-dimensional (3D) cluster of its small cells per multistory building where the optimal size of a 3D cluster of small cells is defined subject to satisfying a predefined co-channel interference threshold both intra-floor and inter-floor levels. We then contribute the following in this paper.

- By presenting a mathematical model for each technique, we formulate the problems for SUIA 1 and SUIA 2 for an arbitrary number of MNOs in a country each operating its in-building small cells at the 28 GHz mmWave spectrum.
- Using the mathematical models, we then derive system-level average capacity, spectral efficiency (SE), and energy efficiency (EE) metrics for an MNO, namely MNO 1, for both SUIA 1 and SUIA 2.
- Extensive simulation and numerical results and analyses are carried out in terms of the average capacity, SE and EE when employing each of these techniques individually, as well as jointly, to small cells per building of MNO 1 to show the impact of each technique, as well as to evaluate the relative performances of SUIA 1 with respect to SUIA 2.
- It is shown that, due to integrating a number of techniques (i.e., spectrum allocation, spectrum sharing, spectrum trading, and spectrum reusing), both SUIA 1 and SUIA 2 outperform each of these techniques when employing individually in terms of SE and EE.
- Finally, it is shown that by applying both approaches SUIA 1 and SUIA 2, the prospective average SE and average EE requirements for sixth-generation (6G) mobile networks can be satisfied.

D. ORGANIZATION
We organize the paper as follows. The system architecture and the proposed approaches SUIA 1 and SUIA 2 are presented in section II. In section III, we present mathematical models for SLSA, FLSA, spectrum sharing, spectrum trading, and spectrum reusing techniques for the 28 GHz mmWave and derive the average capacity, SE, and EE performance metrics for SUIA 1 and SUIA 2. In section IV, we discuss default simulation parameters and assumptions, present numerical and simulation results and analyses for SUIA 1 and SUIA 2, and carry out a comparison for the SE and EE performances of the proposed approaches with regard to that required for 6G mobile systems. We conclude the paper in section V. A list of notations is given in Table 1.

II. SYSTEM ARCHITECTURE AND SPECTRUM UTILIZATION IMPROVEMENT APPROACHES
A. SYSTEM ARCHITECTURE
Assume that four MNOs are operating in a country, and each MNO has a similar system architectural feature including
three types of base stations (BSs), namely macrocell BSs (MBSs), picocell BSs (PBSs), and small cell BSs (SBSs). Hence, like [26], for simplicity, the detailed architecture of only one MNO, i.e., MNO 1, is shown in Fig.1(c). Moreover, SBSs are deployed only within 3-dimensional multistory buildings each serving one UE at a time. 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 propagation characteristics, MBSs and PBSs operate at a low-frequency

| Notation | Description |
|----------|-------------|
| $t$ | Index of a transmission time interval |
| $T$ | Simulation run time with the maximum time of $Q$ |
| $O$ | Number of MNOs of a country |
| $a$ | 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 a resource block |
| $P_{MC}$, $P_{PC}$, $P_{SC}$ | The transmission power of a macrocell, a picocell, and a small cell, respectively |
| $\beta$ | Implementation loss factor |
| $M_{\text{common}}$ | The common spectrum of an MNO $a$ in the pool at any $t_{\text{age}}$ |
| $M_{\text{C,RES}}$ | Countrywide mmWave spectrum in resource blocks |
| $f_{\text{age}}$ | An agreement term to update the licensed spectrum of an MNO |
| $M_{\text{L,RES}}$ | Amount of licensed spectrum in resource blocks of any MNO $a$ at term $t_{\text{age}}$ |
| $M_{\text{DS,RES}}$ | Amount of spectrum in resource blocks of MNO $a$ to serve data traffic at term $t_{\text{age}}$ |
| $M_{\text{RES}}$ | Amount of reserved spectrum in resource blocks for control signaling and other system-specific operations of MNO $a$ at term $t_{\text{age}}$ |
| $S_{l}$ | Number of small cell base stations in any building $l$ |
| $S_{M}$ | Number of macrocell base stations of an MNO |
| $S_{p}$ | Number of picocell base stations per macrocell base station of an MNO |
| $X_{a}$ | A Gaussian random variable with a standard deviation $\Delta$ representing large-scale signal variation due to shadowing |
| $M_{\text{L,RES}}^{\text{opt}}$ | The optimal amount of leased mmWave spectrum in resource blocks for MNO 1 at term $t_{\text{age}}$ in the spectrum trading technique |
| $N_{a}$ | Number of subscribers of an MNO $a$ at term $t_{\text{age}}$ |
| $N_{a,\text{MNO}_1}$ | Number of subscribers of a country at term $t_{\text{age}}$ |
| $l_{\text{intra}, \text{optimal}}$ and $l_{\text{intra}, \text{inner}}$ | Maximum number of co-channel small cells in the intra-floor and inter-floor levels respectively when using the spectrum reusing technique |
| $l_{\text{intra}, \text{optimal}}$ and $l_{\text{inter}, \text{inner}}$ | The optimal value of co-channel interference in the intra-floor and inter-floor levels respectively when using the spectrum reusing technique |
| $d_{\text{min}}$ | The minimum distance between a co-channel small cell and a small cell UE |
| $d_{\text{C,RES}}$, $d_{\text{C,RES}}^{*}$ | The minimum distance between co-channel small cells operating at the 28 GHz mmWave spectrum in the intra-floor level and inter-floor level, respectively |
| $\alpha_{a, \text{C,RES}}$, $d_{\text{floor}}$ | Floor penetration loss at 28 GHz and the height of a floor in a building, respectively |
| $\Theta_{\text{inner, outer}}$ | Maximum number of small cells in the 3D region of exclusion corresponding to satisfying $d_{\text{C,RES}}$ and $d_{\text{C,RES}}^{*}$, respectively |
| $\Theta_{\text{3D}}$, $\gamma$ | The optimal size of a 3D cluster of small cells and the corresponding spectrum reuse factor per multistory building, respectively |
| $\gamma_{a, \text{S,L,RES}}$, $\gamma_{a, \text{S,L,RES}}^{\text{opt}}$ | System-level average capacity, spectral efficiency, and energy efficiency respectively for $L$ buildings of small cells of MNO 1 due to spectrum sharing at any $t_{\text{age}}$ |
| $\gamma_{a, \text{M,L,RES}}$, $\gamma_{a, \text{M,L,RES}}^{\text{opt}}$ | System-level average capacity, spectral efficiency, and energy efficiency respectively for $L$ buildings of small cells of MNO 1 due to spectrum trading at any $t_{\text{age}}$ |
| $\gamma_{a, \text{M,L,RES}}$, $\gamma_{a, \text{M,L,RES}}^{\text{opt}}$ | System-level average capacity, spectral efficiency, and energy efficiency respectively for $L$ buildings of small cells of MNO 1 due to spectrum reusing at any $t_{\text{age}}$ |
| $\gamma_{a, \text{S,L,RES}}$, $\gamma_{a, \text{S,L,RES}}^{\text{opt}}$ | System-level average capacity, spectral efficiency, and energy efficiency respectively for $L$ buildings of small cells of MNO 1 due to spectrum sharing at any $t_{\text{age}}$ |
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| $\gamma_{a, \text{S,L,RES}}$, $\gamma_{a, \text{S,L,RES}}^{\text{opt}}$ | System-level average capacity, spectral efficiency, and energy efficiency respectively for $L$ buildings of small cells of MNO 1 due to spectrum reusing at any $t_{\text{age}}$ |
band, i.e. 2 GHz, whereas all in-building SBSs operate at the 28 GHz mmWave band [26]. Moreover, depending on how the licensed mmWave spectrum is allocated to all four MNOs in the country, i.e. whether or not each MNO is assigned with an equal amount of the mmWave spectrum specified for the country, Fig.1(a) and Fig.1(b) show the proposed approaches to improving the utilization of the licensed mmWave spectrum of MNO 1. Note that the proposed approaches, illustrated in Figs. 1(a) and 1(b), are applicable for all MNOs. We describe both approaches in detail in the following section.

B. PROPOSED SPECTRUM UTILIZATION IMPROVEMENT APPROACHES

Spectrum can be allocated to MNOs in a country either equally or unequally. If the licensed spectrum is allocated equally to each MNO in a country (also termed as static licensed spectrum allocation (SLSA)), it leads to a low...
spectrum utilization. This is because, in practice, the actual number of subscribers varies from one MNO to another, which results in an MNO with more number of subscribers compared to others to suffer from the scarcity of the licensed spectrum, whereas an MNO with less number of subscribers to cause wastage of the licensed spectrum. This can, however, be addressed by redistributing the assigned licensed spectra among MNOs through secondary spectrum trading. In secondary spectrum trading, an MNO with the scarcity of the licensed spectrum can lease the necessary spectrum from other MNOs having unnecessary licensed spectra at the cost of paying the licensing fee of the corresponding leased spectrum, resulting in improving the spectrum utilization of each MNO.

However, without exploiting the secondary-level spectrum trading as described above, the spectrum utilization can be improved even in the primary level by allocating the licensed spectrum unequally to each MNO in accordance with its actual demand, e.g. the number of its subscribers (also termed as flexible licensed spectrum allocation (FLSA)). Besides, in addition to the spectrum allocation techniques described above, the spectrum utilization can be improved further by employing techniques such as spectrum sharing where the licensed spectrum of one MNO can be shared with another, and spectrum reusing where the licensed spectrum of an MNO itself can be reused spatially subject to satisfying certain constraints.

Hence, based on whether or not the licensed mmWave spectrum is allocated equally to each MNO in a country, we propose two spectrum utilization improvement approaches (SUIAs), namely SUIA 1 and SUIA 2. More specifically, SUIA 1 concerns with improving the mmWave spectrum utilization if the licensed mmWave spectrum is allocated equally to each MNO in a country. Whereas, SUIA 2 concerns with improving the mmWave spectrum utilization if the mmWave spectrum is allocated unequally to each MNO. Based on the above discussion, since the secondary spectrum trading is required only when the licensed spectrum is allocated equally to each MNO, as well as spectrum sharing and spectrum reusing techniques can be applied to each approach. SUIA 1 employs SLSA, spectrum trading, spectrum sharing, and spectrum reusing techniques as shown in Fig.1(a), whereas SUIA 2 employs FLSA, spectrum sharing, and spectrum reusing techniques (Fig. 1(b)). All these techniques of both approaches, i.e. SLSA, FLSA, spectrum trading, spectrum sharing, and spectrum reusing, are described in what follows.

1) MILLIMETER-WAVE STATIC LICENSED SPECTRUM ALLOCATION

In the traditional static licensed spectrum allocation (SLSA) technique, the licensed spectrum is allocated to each MNO in a country in an equal amount without taking into account any concern of its actual user demand. The licensed spectrum is typically allocated in large chunks for a long time, which causes not to change the primary spectrum licensee even if the spectrum is underutilized in many areas [11], [27]. Moreover, an MNO is bound to pay for the allocated spectrum even if some portion of the spectrum is left unused. Note that the SLSA applies to only approach 1 of SUIA.

2) MILLIMETER-WAVE FLEXIBLE LICENSED SPECTRUM ALLOCATION

For the flexible licensed spectrum allocation (FLSA), we assume that each MNO is assigned with an amount of licensed 28 GHz mmWave spectrum of a country in accordance with its number of subscribers with respect to that of other MNOs for a certain renewal term. The allocated spectrum to each MNO is updated at each renewal term compliant with its change in the number of subscribers over the previous term subject to satisfying the condition that the effective available countrywide 28 GHz mmWave spectrum is equal to the sum of the licensed spectra allocated to all MNOs. Hence, in FLSA, the mmWave spectrum is allocated to an MNO based on its actual need, i.e. the number of its subscribers, at any renewal term. This results in overcoming the lack of a sufficient amount of spectrum of an MNO to serve its user demand, as well as addressing the issue of the under-utilized or unused spectrum of another MNO, such that the spectrum utilization of all MNOs is improved. Moreover, FLSA allows an MNO to pay the licensing fee only for the amount of spectrum that it needs. Note that the FLSA applies to only approach 2 of SUIA.

3) MILLIMETER-WAVE SPECTRUM SHARING

In both approaches of SUIA, spectrum sharing among the licensed spectra of all MNOs countrywide can be applied. In this regard, we consider that a portion of the mmWave spectrum of each MNO, which is defined in proportionate with the respective amount of allocated spectrum to each MNO, is made common in a pool governed by a central entity such that small cells of MNO 1 in a building can share the licensed mmWave spectrum portion of another MNO in the pool. The central entity can be a time-domain scheduler, which takes control of the allocation of the mmWave spectra of all MNOs in the time-domain subject to avoiding the co-channel interference on the shared spectrum of any MNO in the pool. In this regard, a simplistic approach to avoid co-channel interference is to consider priority-based spectrum allocation such that the primary UEs are always prioritized over the secondary UEs. More specifically, if a small cell UE of any MNO is found within a building, all small cells of MNO 1 within the building can be instructed not to transmit on the shared spectrum of the corresponding MNO in the pool so long as the co-channel UE exists within the building. The time-domain scheduler can simply send a control message to the frequency-domain scheduler of the corresponding building to not schedule small cell UEs of MNO 1 so long as the co-channel UE exists within the building.

Another approach is to employ the almost blank sub-frame (ABS) based enhanced intercell interference coordination (eICIC) by the time-domain scheduler such that all
small cells of MNO 1 within the building transmit only during non-ABSs, while mute their transmissions during ABSs per ABS pattern period (APP) on the shared spectrum of the corresponding MNO so long as the co-channel UE is present within the building. The time-domain scheduler can update the number of ABSs in each APP based on the statistics of the small cell UEs of MNO 1, as well as the co-channel UEs’ of other MNOs and inform the updated ABS pattern to the frequency-domain scheduler of the corresponding building. Both approaches described above have pros and cons, notably, the former approach takes advantage of a less amount of control signaling overheads, however, at the cost of the reduced access to the shared spectrum in the pool and hence the achievable capacity. On the other hand, the latter approach takes advantage of accessing the shared spectrum in the pool more frequently at each APP, however, at the cost of generating more control signaling overheads due to the coordination between the time-domain and the frequency-domain schedulers.

4) MILLIMETER-WAVE SPECTRUM TRADING
Spectrum trading applies only to Approach 1 of SUIA. Recall that the number of subscribers per MNO in a country is not the same such that the SLSA causes a great portion of the licensed spectra of some MNOs either unused or under-utilized. In such a case, to improve the spectral utilization, an MNO with a shortage of spectrum can lease from other MNOs each having unused or under-utilized spectra. Moreover, such type of secondary trading of the licensed spectra can help the buyer MNOs to address their required user demands, whereas the seller MNOs to gain additional profits. Hence, considering that MNO 1 is in shortage of the mmWave spectrum, by exploiting the secondary spectrum trading, MNO 1 can lease exclusively a part of the mmWave spectra of other MNOs who have unused or under-utilized spectra for a certain agreement term $t_{agg}$.

Now, following [26], assume that the amount of the mmWave spectrum required by MNO 1 is proportional to its number of subscribers such that the optimal amount of the leased mmWave spectrum of MNO 1 can be defined based on its number of subscribers with respect to that of other MNOs in the country. This optimal amount of spectrum can be leased from more than one MNOs so long as there exists a common understanding between the seller MNOs and the buyer MNO 1. Note that the optimal amount of spectrum of MNO 1 is updated at each agreement term $t_{agg}$. For example, if at any $t_{agg}$, it is found that the number of subscribers of MNO 1 reduces, MNO 1 can sell its unused spectrum to other MNOs in the country, and vice versa. Hence, the evaluation of the optimal amount of the leased spectrum for MNO 1 is updated iteratively at each $t_{agg}$ such that both the user data demand, as well as the profit from selling the leased spectrum, can be achieved. This results in an improvement in the overall mmWave spectral utilization of all MNOs countrywide.

5) MILLIMETER-WAVE SPECTRUM REUSING
Like spectrum sharing, the spectrum reusing technique can be applied to both approaches of SUIA. Note that high-frequency mmWave signals are frequency-dependent in indoor environments and get attenuated highly because of high distance-dependent path losses, as well as penetration losses from internal walls and floors, of a multistory building. Due to these high losses, the same licensed mmWave spectrum of MNO 1 can be reused to its small cells located within apartments of a multistory building more than once to achieve high spectral utilization. However, reusing the same spectrum of MNO 1 intra-building basis to small cells more than once in a building causes co-channel interference.

In this regard, subject to satisfying a minimum co-channel interference constraint, a minimum distance between co-channel small cells can be defined both intra-floor and inter-floor levels in a building to find a 3D cluster of small cells. The same mmWave spectrum of MNO 1 can then be reused to each 3D cluster of small cells, resulting in reusing the mmWave spectrum of MNO 1 more than once in a building. Moreover, due to the high external wall penetration loss of a building and distance-dependent path loss between adjacent buildings, the mmWave spectrum of MNO 1 can be considered to reuse an inter-building basis, i.e. the mmWave spectrum of MNO 1 can be reused to adjacent buildings of small cells. This way, the mmWave spectrum of MNO 1 can be reused in both the intra-building and inter-building basis depending on the required number of times of reusing the same mmWave spectrum of MNO 1 to improve its mmWave spectrum utilization.

III. PROBLEM FORMULATION
A. PRELIMINARIES
Let $O$ denote the maximum number of MNOs of a country such that $o \in O = \{1, 2, \ldots, O\}$. Let $M_{c,max}$ denote the countrywide total amount of mmWave spectrum in terms of the number of resource blocks (RBs) where an RB is equal to 180 kHz such that each MNO is licensed for a portion of $M_{c,max}$. Let $t_{agg}$ denote an agreement term to update the amount of licensed spectrum of any MNO $o$ ($M_o$) such that at $t_{agg}$, $M_{o,t_{agg}} = \sum_{o=1}^{O} M_{o,t_{agg}} \leq M_{c,max}$. Let $M_{data}$ denote the amount of spectrum in RBs to serve data traffic, whereas $M_{res}^{agg}$ denote the reserved spectrum for control signaling and other system-specific operations of MNO $o$ such that $M_{o,t_{agg}} = (M_{data} + M_{res}^{agg})$ at any $t_{agg}$. Hence, MNO 1 is allocated to the licensed mmWave spectrum of $M_{1,t_{agg}}$ RBs to serve its data traffic with the spectrum of $M_{1,t_{agg}}$. Let $N_{o,t_{agg}}$ denote the total number of subscribers of an MNO $o$ at any $t_{agg}$. Assume that $N_{1,t_{agg}} > N_{2,t_{agg}} > ... > N_{O,t_{agg}}$ such that $\sum_{o} N_{o,t_{agg}} \leq N_{c,max,t_{agg}}$ [26] where $N_{c,max,t_{agg}}$ denotes the maximum number of subscribers of a country at $t_{agg}$.

Assume that for MNO 1, $L$ denotes the number of buildings of small cells per macrancell of MNO 1 such that $l \in \{1, 2, \ldots, L\}$. Further, the number of small cells deployed in each building of MNO 1 is denoted as $S_f$ such that
Let \( S_M \) and \( S_P \) denote respectively the number of MBSs and the number of PBSs per MBS of MNO 1. Also, let \( T \) denote simulation run time with the maximum time of \( Q \) (in time step each lasting 1 ms) such that \( T = \{1, 2, 3, \ldots, Q\} \). Denote \( P_{MC} \), \( P_{PC} \), and \( P_{SC} \) respectively as the transmission power of an MBS, a PBS, and an SBS.

Denote \( \beta \) as the implementation loss factor such that using Shannon’s capacity formula, a link throughput at RB= \( i \) in transmission time interval (TTI)= \( t \) in bps per Hz is given by [26],

\[
\sigma_{t,i}(\rho_{t,i}) = \begin{cases} 
0, & \rho_{t,i} < -10 \text{ dB} \\
\beta \log_2 \left(1 + 10^{(\rho_{t,i}(\text{dB})/10)}\right), & -10 \text{ dB} \leq \rho_{t,i} \leq 22 \text{ dB} \\
4.4, & \rho_{t,i} > 22 \text{ dB} 
\end{cases} \tag{1}
\]

Let \( N_{1,\text{MBS}} \) denote the number of UEs, whereas \( M_{1,\text{MBS}} \) denote the operating spectrum in RBs, per macrocell of MNO 1 such that, following [26], the total capacity of all macrocell UEs of MNO 1 is given by,

\[
\sigma_{1,\text{MBS}} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{1,\text{MBS}}} \sigma_{t,i}(\rho_{t,i}) \tag{2}
\]

where \( \sigma \) and \( \rho \) are responses over \( M_{1,\text{MBS}} \) RBs of macrocell UEs of MNO 1 in \( t \) at \( T \).

### B. FLSA

Recall that, in FLSA, the amount of licensed spectrum allocated to an MNO \( o \) is proportional to its number of subscribers. Then, the optimal amount of licensed spectrum \( M_{o,\text{agg}} \) in RBs for an MNO \( o \in O \) at term \( t_{\text{agg}} \) can be found by solving the following problem.

\[
\min_{o \in O} M_{o,\text{agg}} \\
\text{subject to (a)} \forall o \forall t_{\text{agg}} \sum_{o} N_{o,\text{agg}} \leq N_{C,\text{max,agg}} \\
\text{(b)} \forall o \forall t_{\text{agg}} \sum_{o} M_{o,\text{agg}} \leq M_{C,\text{max}} \tag{3}
\]

The solution of the above optimization problem for the optimal amount of licensed 28 GHz mmWave spectrum for an MNO \( o \) at each term \( t_{\text{agg}} \) can be found as follows. Since the number of subscribers of all MNOs is not the same at any \( t_{\text{agg}} \), assume that \( N_{1,\text{agg}} > N_{2,\text{agg}} > \ldots > N_{O,\text{agg}} \) at \( t_{\text{agg}} \) such that the constraint 3(a) is satisfied. Since the amount of licensed spectrum allocated to an MNO \( o \) is proportional to its number of subscribers \( N_{o,\text{agg}} \) at any \( t_{\text{agg}} \), the optimal amount of licensed 28 GHz mmWave spectrum in RBs needed for an MNO \( o \) to serve its subscribers \( N_{o,\text{agg}} \) at any \( t_{\text{agg}} \) is given by,

\[
M_{o,\text{agg}} = \left( \frac{N_{o,\text{agg}} \times M_{C,\text{max}}}{N_{C,\text{max,agg}}} \right) o \in O \tag{4}
\]

The same process described above is applicable for all MNOs at each term \( t_{\text{agg}} \) to update flexibly the on-demand basis allocation of the licensed 28 GHz mmWave spectrum.

### C. SLSA

Assume that each MNO is licensed exclusively for an equal amount of mmWave spectrum of \( M \) RBs at any term \( t_{\text{agg}} \) in SLSA such that we can write the following for the allocated spectrum of any MNO \( o \).

\[
M_{o,\text{agg}} = M \tag{6}
\]

### D. SPECTRUM SHARING

We consider the priority-based spectrum allocation to share the mmWave spectra of other MNOs in the common pool with small cells per building of MNO 1. Let the portion of the mmWave spectrum of each MNO that is made common in the pool at any \( t_{\text{agg}} \) is denoted by \( M_{o,\text{agg}} \) such that the total mmWave spectrum available in the common pool is given by \( \sum_{o=1}^{O} M_{o,\text{agg}} \).

Assume that the average duration of the presence of UEs in a building of small cells of MNOs other than MNO 1 (i.e., \( O \setminus \{1\} = \{2, \ldots, O\} \)) in \( T = Q \) is given by \( \{Q_2, \ldots, Q_O\} \) at any \( t_{\text{agg}} \). Hence, \( M_{\text{agg}} \) can share the mmWave spectra \( \{M_{2,\text{agg}} \text{,} \ldots, M_{O,\text{agg}}\} \) of other MNOs \( \{2, \ldots, O\} \) in \( T = Q \) for an average duration of \( (Q - Q_2) \ldots (Q - Q_O) \) at any \( t_{\text{agg}} \). Since small cells of MNO 1 per building operate at its licensed mmWave spectrum of \( M_{\text{agg}} \) RBs at any \( t_{\text{agg}} \) to serve its data traffic in all \( T \) TTIs, the total capacity served by a small cell of MNO 1 due to spectrum sharing (SS) at any \( t_{\text{agg}} \) is given by,

\[
\sigma_{1,\text{agg}}^{\text{SS}} \left( \sum_{o=2}^{O} \sum_{i=1}^{M_{o,\text{agg}}} \sigma_{t,i}(\rho_{t,i}) \right) + \left( \sum_{o=2}^{O} \sum_{i=1}^{M_{o,\text{agg}}} \sigma_{t,i}(\rho_{t,i}) \right) \tag{7}
\]

The aggregate capacity per 3D building of \( S_f \) small cells at any \( t_{\text{agg}} \) is then given by,

\[
\sigma_{1,\text{agg}}^{\text{SS}} = \sum_{s=1}^{S_f} \sigma_{1,\text{agg}}^{\text{SS}} \tag{8}
\]

We assume that the indoor propagation characteristics in each building do not differ considerably from one another such that using linear approximation, the average capacity for \( L \) buildings of small cells of MNO 1 at any \( t_{\text{agg}} \) can be roughly given by,

\[
\sigma_{1,\text{agg}}^{\text{SS}} \left( \frac{L}{S_f} \right) \sum_{s=1}^{S_f} \sigma_{1,\text{agg}}^{\text{SS}} \tag{9}
\]

The system-level capacity of MNO 1 including all UEs at any \( t_{\text{agg}} \) is then given by,

\[
\sigma_{1,\text{agg}}^{\text{SS, cap}} = \sigma_{1,\text{agg}}^{\text{SS}} + \sigma_{1,\text{agg}}^{\text{SS}} \tag{10}
\]

Now, the spectral efficiency for \( L \) buildings at any \( t_{\text{agg}} \) is given by,

\[
\sigma_{1,\text{agg}}^{\text{SS, SE}} = \frac{\sigma_{1,\text{agg}}^{\text{SS, cap}}}{(M_{1,\text{MBS}} + M_{1,\text{agg}})} \tag{11}
\]
Similarly, the energy efficiency at any $t_{agg}$ is given by,

$$\sigma^{SS,EE}_1, L_{agg} = \left( \left( L \times S_F \times P_{sc} \right) + \left( S_p \times P_{pc} \right) + \left( S_M \times P_{mc} \right) \right) / \left( \sigma^{SS,\cap}_1, L_{agg} / Q \right)$$ \hspace{1cm} (12)

Remark 1: For estimating the SE of MNO 1 due to spectrum sharing in (11), we consider only the spectrum that is licensed by MNO 1 exclusively at the expense of the cost for licensing the corresponding spectrum. Since in the shared spectrum pool described above, one MNO can share mutually the common mmWave spectrum of another at no cost, but under a mutual understanding among each other, the shared common mmWave spectrum of other MNOs is not considered for estimating the SE of MNO 1.

E. SPECTRUM TRADING

Recall that, in spectrum trading, the amount of mmWave spectrum required to serve small cell UEs of MNO 1 is proportional to its number of subscribers $N_{1,agg}$. Then, the required amount of mmWave spectrum for MNO 1 to serve its data traffic can be found as follows.

$$M_{1,agg}^{\text{required}} = \left( N_{1,agg} \times \sum_{\alpha=1}^{O} M_{agg}^{\text{data}, \alpha} \right) / \sum_{\alpha=1}^{O} N_{agg, \alpha}$$ \hspace{1cm} (13)

Hence, the optimal amount of leased mmWave spectrum for MNO 1 at an agreement term $t_{agg}$ is given by,

$$M_{1,agg}^{\text{leased}^*} = M_{1,agg}^{\text{required}} - M_{1,agg}^{\text{data}}$$ \hspace{1cm} (14)

In the above equation, $M_{1,agg}^{\text{leased}^*}$ is negative if MNO 1 has an excess of mmWave spectrum of $M_{1,agg}^{\text{leased}^*}$ even after serving its small cell user demand, whereas $M_{1,agg}^{\text{leased}^*}$ is positive if MNO 1 lacks the additional mmWave spectrum of $M_{1,agg}^{\text{leased}^*}$ to serve its small cell user demand [26]. The value of $M_{1,agg}^{\text{leased}^*}$ is updated at each agreement term $t_{agg}$ to serve the user traffic of MNO 1 on-demand basis.

Similarly, following (7)-(12), the system-level average capacity, SE, and EE for $L$ buildings at an agreement term $t_{agg}$ due to spectrum trading (ST) can be given respectively as follows.

$$\text{ST,\cap} \sigma^{1, L_{agg}} = \sigma^{1, MBS} + \left( L \times \sum_{s=1}^{S_F} \sum_{i=1}^{T} \sum_{\alpha=1}^{O} \left( M_{agg}^{\text{data}, \alpha} \times M_{agg}^{\text{leased}^*} \right) \rho^{\alpha}_{\text{agg}} \right) \hspace{1cm} (15)$$

$$\text{ST,SE} \sigma^{1, L_{agg}} = \sigma^{1, L_{agg}} / \left( \left( M_{1,agg}^{\text{MBS}} + M_{1,agg}^{\text{leased}^*} \right) \times Q \right) \hspace{1cm} (16)$$

$$\text{ST,EE} \sigma^{1, L_{agg}} = \left( L \times S_F \times P_{sc} \right) + \left( S_p \times P_{pc} \right) + \left( S_M \times P_{mc} \right) / \left( \sigma^{1, L_{agg}} / Q \right) \hspace{1cm} (17)$$

F. SPECTRUM REUSING

For the 28 GHz mmWave path-loss estimation, we consider the omnidirectional multi-frequency combined polarization close-in free space reference distance with frequency-dependent path loss exponent (CIF) large-scale 28 GHz mmWave path-loss model given as follows [28].

$$PL \text{ (dB)} = 61.38 + 17.97 \log_{10}(d) + X_{\Delta}$$ \hspace{1cm} (18)

where $X_{\Delta}$ denotes the Gaussian random variable with a standard deviation $\Delta$ representing large-scale signal variation due to shadowing.

Let $I_{\text{max, intra}}$ and $I_{\text{max, inter}}$ denote respectively the maximum number of co-channel small cells in the intra-floor and inter-floor levels in a multistory building of small cells. Let, also, $I_{\text{optimal, intra}}$ and $I_{\text{optimal, inter}}$ denote respectively the optimal value of co-channel interference in the intra-floor and inter-floor levels. If $d_{\text{min}}$ denotes the minimum distance between a co-channel small cell and a small cell UE, then, following [29] and using (18), the minimum distance between co-channel small cells operating at the 28 GHz mmWave spectrum in the intra-floor level and inter-floor level can be expressed respectively as follows.

$$d_{\text{CCL, intra}}^* = d_{\text{min}} \times \left( I_{\text{max, intra}} / I_{\text{optimal, intra}} \right)^{1.797^{-1}}$$ \hspace{1cm} (19)

$$d_{\text{CCL, inter}}^* \geq d_{\text{min}} \times \left( 10^{-0.1a_{\text{floor}} (d_{\text{CCL, inter}})} \times \left( I_{\text{max, inter}} / I_{\text{optimal, inter}} \right) \right)^{1.797^{-1}}$$ \hspace{1cm} (20)

where $a_{\text{floor}} (d_{\text{CCL, inter}})$ denotes the floor penetration loss at 28 GHz, which is 55 dB for the first floor as a worst-case analysis [29]. Hence, using (19)-(20), no reuse of the same 28 GHz mmWave spectrum can be possible to small cells that fall within $d_{\text{CCL, intra}}^*$ and $d_{\text{CCL, inter}}^*$ in the intra-floor and the inter-floor levels respectively such that a 3D region of exclusion for reusing the same mmWave can be formed as follows.

Let $\Theta_{\text{intra}}$ and $\Theta_{\text{inter}}$ denote the maximum number of small cells in the 3D region of exclusion corresponding to satisfying $d_{\text{CCL, intra}}^*$ and $d_{\text{CCL, inter}}^*$ respectively, which can be given by,

$$\Theta_{\text{intra}} = \left( \text{ceil} \left( d_{\text{CCL, intra}}^* / \left( a / 2 \right) \right) \right)^2$$ \hspace{1cm} (21)

$$\Theta_{\text{inter}} = \text{ceil} \left( d_{\text{CCL, inter}}^* / d_{\text{floor}} \right)$$ \hspace{1cm} (22)

where $a$ denotes the side length of 10 m of a square apartment and $d_{\text{floor}}$ denotes the height of a floor in a building such that the optimal size of a 3D cluster of small cells can be expressed as follows.

$$\Theta_{3D} = \left( \Theta_{\text{intra}} \times \Theta_{\text{inter}} \right)$$ \hspace{1cm} (23)

Let $\gamma$ denote the spectrum reuse factor per multistory building of small cells corresponding to $\Theta_{3D}$ such that it can be expressed as follows.

$$\gamma = S_F / \Theta_{3D}$$ \hspace{1cm} (24)
Let $S_{F,cl}$ denote the maximum number of small cells per 3D cluster of a size $\Phi_{3D}$ such that $s \in \{1, 2, \ldots, S_{F,cl}\}$. Then, following (7)-(12), the system-level average capacity, SE, and EE for $L$ buildings of small cells due to spectrum reusing (SR) at any $t_{agg}$ can be given respectively as follows.

$$
\sigma_{1,L,t_{agg}}^{SR,\text{cap}} = \sigma_{1,MBS} + \left( L \times \gamma \times \sum_{s=1}^{S_{F,cl}} \sum_{t \in T} M_{t,\text{agg}}^{\text{data}} \sigma_{1,s,t,1}^{agg} \left( \rho_{1,s,t,1} \right) \right)
$$

(25)

$$
\sigma_{1,L,t_{agg}}^{SR,\text{SE}} = \sigma_{1,L,t_{agg}}^{SR,\text{cap}} / \left( (M_{1,MBS} + M_{1,t_{agg}}) \times Q \right)
$$

(26)

$$
\sigma_{1,L,t_{agg}}^{SR,\text{EE}} = \left( \left( L \times S_{F} \times P_{SC} \right) + \left( S_{P} \times P_{PC} \right) \right) / \left( \sigma_{1,L,t_{agg}}^{SR,\text{cap}} / Q \right)
$$

(27)

Detailed modeling of the spectrum reusing technique described above is out of the scope of this paper, which can be found in [29].

**G. SUIA1**

1) SUIA 1

Recall that SUIA 1 employs SLSA, spectrum sharing, spectrum trading, and spectrum reusing techniques. Hence, by applying these techniques described above to small cells per building of MNO 1 simultaneously, the system-level average capacity, SE, and EE in SUIA 1 for any value of $\gamma$ with the variation of the number of buildings of small cells $L$ at an agreement term $t_{agg}$ can be given as follows.

$$
\sigma_{1,L,t_{agg}}^{\text{SUIA1, cap}}(L) = \sigma_{1,MBS} + \left( L \times \gamma \times \left( \sum_{s=1}^{S_{F,cl}} \sum_{t \in T} \left( M_{t,\text{agg}}^{\text{data}} + M_{t,\text{agg}}^{\text{leased}} \right) \sigma_{1,s,t,1}^{agg} \left( \rho_{1,s,t,1} \right) \right) \right)
$$

(28)

$$
\sigma_{1,L,t_{agg}}^{\text{SUIA1, SE}}(L) = \sigma_{1,L,t_{agg}}^{\text{SUIA1, cap}}(L) / \left( (M_{1,MBS} + M_{1,t_{agg}}) \times Q \right)
$$

(29)

$$
\sigma_{1,L,t_{agg}}^{\text{SUIA1, EE}}(L) = \left( \left( L \times S_{F} \times P_{SC} \right) + \left( S_{P} \times P_{PC} \right) \right) / \left( \sigma_{1,L,t_{agg}}^{\text{SUIA1, cap}}(L) / Q \right)
$$

(30)

2) SUIA 2

However, SUIA 2 employs FLSA, spectrum sharing, and spectrum reusing techniques. Hence, by applying these techniques described above to small cells per building of MNO 1 simultaneously, the system-level average capacity, SE, and EE in SUIA 2 for any value of $\gamma$ with the variation of $L$ at an agreement term $t_{agg}$ can be given as follows.

$$
\sigma_{1,L,t_{agg}}^{\text{SUIA2, cap}}(L) = \sigma_{1,MBS} + \left( L \times \gamma \times \left( \sum_{s=1}^{S_{F,cl}} \sum_{t \in T} M_{t,\text{agg}}^{\text{data}} \sigma_{1,s,t,1}^{agg} \left( \rho_{1,s,t,1} \right) \right) \right)
$$

(31)

$$
\sigma_{1,L,t_{agg}}^{\text{SUIA2, SE}}(L) = \sigma_{1,L,t_{agg}}^{\text{SUIA2, cap}}(L) / \left( (M_{1,MBS} + M_{1,t_{agg}}) \times Q \right)
$$

(32)

$$
\sigma_{1,L,t_{agg}}^{\text{SUIA2, EE}}(L) = \left( \left( L \times S_{F} \times P_{SC} \right) + \left( S_{P} \times P_{PC} \right) \right) / \left( \sigma_{1,L,t_{agg}}^{\text{SUIA2, cap}}(L) / Q \right)
$$

(33)

**IV. PERFORMANCE EVALUATION**

**A. SIMULATION PARAMETERS AND ASSUMPTIONS**

Table 2 shows simulation parameters and assumptions considered for the performance evaluation of the proposed SUIA1s, which are in accordance with the recommendations from the 3rd generation partnership project (3GPP) and International Telecommunication Union-Radiocommunication Sector (ITU-R) standardization bodies. As one of the potential mmWave bands for 5G and upcoming 6G [30], the 28 GHz band is considered. Moreover, for simplicity, we consider countrywide 200 MHz spectrum to evaluate the performance of the proposed SUIA1s though the 28 GHz mmWave spectrum assigned for a country can be huge (e.g., in the GHz level [31]). Since the launch of 5G mobile networks is in its very early stage, experimental results related to the proposed approaches on 5G networks in the existing literature are not obvious. Hence, the performances of the proposed approaches, detailed conceptually, and analyzed numerically in the previous sections, are evaluated in an appropriate simulation environment using the assumptions and parameters given in Table 2. Further, the SE and EE performances of the proposed approaches are compared with that expected for 6G mobile networks.

Since an SBS usually covers a small group of users, and RBs are allocated orthogonally by any Proportional Fair scheduler to small cell UEs of an MNO, the overall system-level capacity and other associated performance metrics are not affected by the change in the number of active small cell UEs (i.e., small cell UE density) per SBS. Moreover, the speed of a UE in the indoor environment is very low such that the channel variation at this speed can be considered negligible for a line-of-sight (LOS) 28 GHz mmWave channel. That's why, even though the proposed approaches can be investigated for the case of multiple UEs served simultaneously by an SBS, as well as the variation in the small cell UE mobility, the variation in the density per SBS, as well as the
mobility, of small cell UEs within a building are not taken into account due to their insignificant impact on the overall performances of the proposed approaches. Instead, we consider a particular scenario of the density and mobility of small cell UEs, including serving one small cell UE by an SBS at a time and the speed of a pedestrian user of 3 km/hr [32]–[34], respectively, to keep the overall performance analysis simple. Numerous existing literature has also considered a similar assumption of the user density of one UE per SBS such as [32]–[35], as well as the stationary user mobility such as [36], for the performance analysis.

Besides, like [37], we also exploit all three domains, i.e., frequency, time, and space, to measure the spectrum utilization. More specifically, the spectrum allocation technique exploits the frequency-domain to allocate the 28 GHz spectrum among MNOs countrywide. The dynamic spectrum sharing, as well as spectrum trading, techniques exploit both the time and frequency domains to utilize efficiently the unused or underutilized spectrum of MNOs in a country. Further, the spectrum reusing technique exploits the space-domain to reuse the 28 GHz mmWave spectrum of any MNO in any 3D multistory building. Hence, by exploiting all three domains, the available 28 GHz mmWave spectrum of each MNO is utilized as best as possible to serve the maximum possible user data of the corresponding MNO. Moreover, since the spectrum utilization has a direct impact on the average capacity, SE, and EE metrics, the performance of the proposed SUIA approaches to improve the spectrum utilization of the 28 GHz mmWave is considered to evaluate in terms of these metrics. The same practice has also been adopted in the existing literature to evaluate the spectrum utilization performance in terms of the capacity and SE metrics. For example, the authors in [38]–[42] have evaluated the spectrum utilization performance in terms of the SE metric.

**FIGURE 2.** Performance responses of MNOs in SUIA 1 and SUIA 2 for γ = 6: (a) average capacity, (b) SE, and (c) EE.
TABLE 2. Simulation parameters and assumptions.

| Parameters and Assumptions                                      | Value                                                                 |
|-----------------------------------------------------------------|----------------------------------------------------------------------|
| Total 28 GHz spectrum and reserved 28 GHz spectrum per MNO    | 50 MHz and 10 MHz, 10 MHz                                           |
| Countrywide total number of MNOs and subscribers\(^1\)          | 4 and \(N_c\text{-max}\)                                           |
| Number of subscribers for MNOs 1, 2, 3, and 4 respectively\(^2\) | 40%, 30%, 20%, and 10% of \(N_c\text{-max}\)                         |
| E-UTRA simulation case\(^1\)                                   | 3GPP case 3                                                         |
| Cellular layout\(^2\), Inter-site distance (ISD)\(^3\), transmit | Hexagonal grid, dense urban, 3 sectors per macrocell site, 1732 m, and|
| Carrier frequency\(^2\)                                        | Licensed 2 GHz non-LOS (NLOS) microwave spectrum band for macrocells and picocells, licensed 28 GHz LOS mmWave spectrum band for small cells |
| Number of cells                                                 | 1 macrocell, 2 picocells, 48 small cells per building               |
| Total BS transmit power\(^2\) (dBm)                            | 46 for macrocell\(^4\), 37 for picocells\(^1\), 19 for 28 GHz for small cells\(^5\) |
| Co-channel small-scale fading model\(^2\)                      | Frequency selective Rayleigh for 2 GHz, no small-scale fading for 28 GHz |
| External wall penetration loss\(^2\) (\(L_{ew}\))               | 20 dB for 2 GHz spectrum                                           |
| MBS and a UE\(^1\)                                              | PL(db)=\(-15.3 + 37.6 \log_10 R\), R is in m                       |
| Outdoor macrocell UE                                            | PL(db)=\(-15.3 + 37.6 \log_10 R + L_{ew}\), R is in m              |
| PBS and a UE\(^1\)                                             | PL(db)=\(-140.7 + 36.7 \log_10 R\), R is in km                    |
| SBS and a UE\(^2\)                                             | PL(db)=\(-61.38 + 17.97 \log_10 R\), R is in m                    |
| Lognormal shadowing standard deviation (dB)                     | 8 for MBS\(^1\), 10 for PBS\(^1\), and 9.9 for 28 GHz LOS spectrum for SBS\(^2\) |
| Outdoor macrocell UE                                            | L                                                              |
| Number of buildings L                                           | 6                                                               |
| Number of floors per building                                 | 8                                                               |
| Number of apartments per floor                                  | 1                                                                |
| Total number of SBSs per building                              | 48                                                               |
| Area of an apartment 10\(^1\) \(\times\) 10 \(\times\) m\(^2\)  | 40 m (radius), 2/15                                               |
| Number of buildings L                                           | 35%                                                             |
| Number of floors per building                                  | 6                                                               |
| Number of apartments per floor                                  | 8                                                               |
| Number of SBSs per apartment                                    | 1                                                                |
| Total number of SBSs per building                              | 48                                                               |
| Scheduler and traffic model\(^2\)                             | Proportional Fair and full buffer                                  |
| Type of SBSs                                                    | Closed Subscriber Group (CSG) femtocell BSs                        |
| Channel State Information(CSI)                                  | Ideal                                                            |
| \(Q_1, Q_2, Q_3, Q_4\) in the spectrum sharing technique      | 50% of \(Q\) for each MNO                                        |
| Shared mmWave spectrum of an MNO \(o\) in the pool at any \(t_{bs}\), i.e., \(M_{c,max}\) | 40% of the licensed spectrum of the MNO \(o\), i.e., \(M_{c,max}\) |
| TTI, scheduler time constant \(t_{sch}\), \(t_{sec}\)          | 1 ms, 100 ms, 6 months                                           |
| Total simulation run time \(t_{sim}\)                          | 8 ms                                                             |

\(^1\) from [43], \(^2\) from [44], \(^3\) from [45], \(^4\) from [46], \(^5\) from [28], \(^6\) from [47], \(^7\) from [26].

B. PERFORMANCE RESULTS

In SUIA 2, MNO 1 is assigned with the maximum, whereas MNO 4 is assigned with the minimum, amount of the licensed mmWave spectrum. These cause MNO 1 to achieve the maximum capacity while MNO 4 to achieve the minimum capacity in SUIA 2 (Fig. 2(a)). Since the EE is inversely related to the achievable capacity, MNO 1 provides the best EE (i.e., the minimum energy required per bit transmission), while MNO 4 provides the worst EE, performances (Fig. 2(c)). However, the response of the SE of an MNO is not straightforward as the SE is a function of the achievable capacity, as well as the available spectrum bandwidth, of an MNO.

In this regard, the overall achievable capacity for an MNO in SUIAs depends on both its licensed mmWave spectrum, as well as the shared mmWave spectrum in the common pool. Since each MNO shares a portion (i.e., 40%) of its licensed mmWave spectrum, an MNO assigned with a more licensed mmWave spectrum shares more to the common pool of the mmWave spectrum than others, whereas can use less shared mmWave spectrum in the pool. Since the total mmWave spectrum that can be used to obtain capacity is the summation of both the licensed mmWave spectrum and the shared mmWave spectrum for an MNO, and MNO 1 can use the minimum amount of the shared spectrum, MNO 1 can achieve the maximum capacity at the expense of more
TABLE 3. Required values of $L$ to satisfy both average SE and EE requirements for 6G mobile systems for $\gamma = 6$.

| Proposed Approach | MNO       | $L$ (to satisfy both average SE and EE requirements for 6G mobile systems) |
|-------------------|-----------|--------------------------------------------------------------------------|
|                   | MNO 1     | $\sigma_{\text{SE},L}^{\text{mmWave}} (L) \geq \sigma_{\text{SE},L}^{\text{6G}}$ | $\sigma_{\text{EE},L}^{\text{mmWave}} (L) \leq \sigma_{\text{EE},L}^{\text{6G}}$ | $\max \left( \sigma_{\text{SE},L}^{\text{mmWave}} (L), \sigma_{\text{EE},L}^{\text{mmWave}} (L) \right)$ |
| SUIA 1            | MNO 1     | 3  | 1  | 3 |
|                   | MNO 2     | 4  | 1  | 4 |
|                   | MNO 3     | 4  | 1  | 4 |
|                   | MNO 4     | 3  | 1  | 3 |
| SUIA 2            | MNO 1     | 5  | 1  | 5 |

The same explanation as above for MNO 1 applies to all MNOs. For example, since MNO 4 is assigned with the minimum amount of the licensed mmWave spectrum, whereas can use the maximum amount of the shared mmWave spectrum, MNO 4 provides the best SE response (Fig.2(b)). Recall that we consider only the licensed spectrum, not the shared spectrum, to estimate the SE of an MNO. Like MNO 1 and MNO 4, MNO 2 and MNO 3 show similar average capacity, SE, and EE responses such that their responses fall within that of MNO 1 and MNO 4 as shown in Fig.2.

Moreover, from Fig.2(c), it can be found that the EE response of any MNO, e.g. MNO 1, (as each MNO in SUIA 1 is assigned with an equal amount of the licensed mmWave spectrum) in SUIA 1 does not deviate significantly from that of any MNO, particularly an MNO assigned with the maximum amount of the licensed spectrum (i.e., MNO 1) in SUIA 2. However, the SE response of any MNO in SUIA 1 lies between that of MNOs, particularly MNOs assigned with the minimum amount of the licensed spectrum (i.e., MNO 4 and MNO 3) in SUIA 2 as shown in Fig.2(b). Overall, SE and EE performances of an MNO in SUIA 1 do not differ considerably from that in SUIA 2 even though their underlying processes differ considerably from one to another. Hence, depending on the spectrum allocation policies and practices in a country, either SUIA 1 or SUIA 2 can be employed to improve the spectrum utilization of MNOs in a country.

In general, when flexibility and liberation in spectrum usage rights are of the major concern, SUIA 2 is preferable to SUIA 1 since it takes advantage of the spectrum liberalization to great extent by avoiding the tedious and complex market-based spectrum management approaches such as the auction for the primary spectrum allocation and the secondary spectrum trading [48]. Moreover, it allows an MNO to pay the licensing fee only for the amount of licensed spectrum that it needs. In this regard, the national regulatory agency or any third-party can regulate updating the allocated spectrum to each MNO at each renewal term.

Now, to show the impact of component techniques for an MNO in both SUIA 1 and SUIA 2, Fig.3 shows the SE and EE performances of all techniques for MNO 1 in SUIA 1 and SUIA 2. From Fig.3, it can be found that the spectrum reusing technique outperforms the spectrum sharing (as well as spectrum trading in SUIA 1) technique significantly in both SUIA 1 and SUIA 2 in terms of the SE and EE performances. This can be justified by the fact that the licensed mmWave spectrum for the data traffic of MNO 1 in both approaches can be reused to small cells deployed in 3D space within a multistory building more than once. By changing the size of the 3D cluster of small cells, $\gamma$ can be varied.
In general, the smaller the size of the 3D cluster, the higher the achievable SE and EE. However, for spectrum sharing, as well as spectrum trading (in SUIA 1 only), techniques, the SE and EE performances depend respectively on the actual amount of the shared spectra and the leased spectra of other MNOs with MNO 1. Overall, as compared to other techniques, both SUIA 1 and SUIA 2 are mainly influenced by the spectrum reusing technique, which can be varied by changing the value of $\gamma$.

C. PERFORMANCE COMPARISON

It is expected that the future 6G mobile networks can achieve 10 times average SE (i.e., 270-370 bps/Hz), as well as 10 times average EE (i.e., 0.3 $\mu$J/b), of 5G mobile networks [49]. Let $\sigma_{SE}^{6G}$ and $\sigma_{EE}^{6G}$ respectively as the average SE and average EE requirements for 6G such that $\sigma_{SE}^{6G} = 370$ bps/Hz and $\sigma_{EE}^{6G} = 0.3 \mu$J/b. From Fig. 2, it can be found that to satisfy both the SE and EE requirements for 6G mobile networks, the number of buildings of small cards $L$ required by any MNO in SUIA 1 is 3, whereas, by MNO 1, MNO 2, MNO 3, and MNO 4 in SUIA 2 are respectively 5, 4, 4, and 3 as shown in Table 3. Hence, the required value of $L$ does not vary significantly for any MNO in SUIA 1 and SUIA 2 to satisfy both the SE and EE requirements for 6G. Overall, any MNO in the proposed SUIA 1 and SUIA 2 can achieve the SE and EE requirements for 6G mobile systems by reusing the 28 GHz mmWave spectrum to just 3 to 5 buildings of its small cells located over the coverage of a macrocell of the MNO.

V. CONCLUSION

Radio spectrum is expensive and limited and hence improving the utilization of the available licensed spectrum is one of the major concerns of a mobile network operator (MNO) to address the ever-increasing high user data rates and capacity demands of the current and the next-generation mobile networks. In this regard, spectrum allocation, sharing, trading, and reusing techniques play a significant role in enhancing the utilization of the spectrum of an MNO in a country. Though spectrum allocation, spectrum sharing, spectrum trading, and spectrum reusing techniques have been studied discretely in the existing literature, exploiting all these techniques together, particularly for the licensed 28 GHz mmWave spectrum of any MNO in a country using in-building small cells, to improve the utilization of the 28 GHz mmWave spectrum has not been addressed yet.

In addressing so, in this paper, we have proposed two spectrum utilization improvement approaches (SUIAs), namely SUIA 1 and SUIA 2, based on whether or not the licensed 28 GHz mmWave spectrum is allocated equally to each MNO in a country. SUIA 1 concerns with improving the 28 GHz mmWave spectrum utilization if the licensed 28 GHz mmWave spectrum is allocated equally to each MNO in a country in a static manner, also termed as static licensed spectrum allocation (SLSA). Whereas, SUIA 2 concerns with improving the 28 GHz mmWave spectrum utilization if the mmWave spectrum is allocated unequally to each MNO flexibly for a certain renewal term in accordance with its number of subscribers, also termed as flexible licensed spectrum allocation (FLSA). Since sharing and reusing of the licensed spectrum allocated to each MNO using either SLSA or FLSA can be exploited, and the secondary spectrum trading is required only in case of SLSA to redistribute the statically assigned licensed spectra among MNOs, SUIA 1 employs SLSA, spectrum trading, spectrum sharing, and spectrum reusing techniques, whereas SUIA 2 employs FLSA, spectrum sharing, and spectrum reusing techniques.

We have described the system architecture and the concept of SLSA, FLSA, spectrum sharing, spectrum trading, and spectrum reusing techniques. Further, we have presented mathematical models for these techniques and derived average capacity, SE, and EE performance metrics for SUIA 1 and SUIA 2. Extensive numerical and simulation results and analyses for SUIA 1 and SUIA 2 have been carried out in terms of the average capacity, SE and EE when employing each of these techniques individually, as well as jointly, to small cells per building of MNO 1. Regarding the impact of component techniques, it has been found that both SUIA 1 and SUIA 2 are mainly influenced by the spectrum reusing technique as compared to others. Further, in SUIA 2, each MNO shares a portion of its licensed spectrum such that an MNO assigned with the maximum licensed spectrum can use the minimum amount of the shared spectrum while achieving the maximum EE and the minimum SE since the total spectrum that can be used to obtain capacity is the summation of both the licensed spectrum and the shared spectrum for an MNO. However, in SUIA 1, since each MNO is assigned with an equal amount of the licensed spectrum, SE and EE responses for all MNOs are the same.

Overall, it has been found that SE and EE performances of an MNO in SUIA 1 do not differ considerably from that in SUIA 2 even though their underlying processes differ considerably from one to another. Hence, depending on the spectrum allocation policies and practices in a country, either SUIA 1 or SUIA 2 can be employed. For example, when the flexibility and liberation in spectrum usage rights are of the major concern, SUIA 2 is preferable to SUIA 1 since it takes advantage of spectrum liberalization to great extent, whereas allows an MNO to pay the licensing fee only for the amount of licensed spectrum that it needs. Finally, it has been shown that any MNO in the proposed SUIA 1 and SUIA 2 can achieve the SE and EE requirements for sixth-generation (6G) mobile systems by reusing the 28 GHz mmWave spectrum to just 3 to 5 buildings of its small cells located over the coverage of a macrocell of the MNO.

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