Research Article

Dynamic Allocation and Sharing of Millimeter-Wave Spectrum with Indoor Small Cells in Multioperator Environments toward 6G

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In this article, we propose a two-level dynamic spectrum allocation and sharing (DSAS) technique to address both spectrum liberalization and spectrum flexibility for more progressive spectrum management so as to improve the countrywide spectrum utilization of the 28-GHz millimeter-wave (mmWave). More specifically, to liberalize allocating countrywide spectrum to MNOs, in level 1 (i.e., primary) spectrum allocation (PSA), each mobile network operator (MNO) is assigned with an amount of 28-GHz spectrum corresponding to its number of subscribers for a certain spectrum renewal term, whereas, to exploit spectrum flexibility, in level 2 (i.e., secondary) spectrum sharing (SSS), when no user equipment is present inside the building, the allocated spectrum to an MNO in PSA is allowed to share with small cells of another MNO in a building. We estimate the amount of spectrum for each MNO in both PSA and SSS. We derive system-level average capacity, spectral efficiency (SE), energy efficiency (EE), and cost efficiency (CE) for the proposed DSAS technique, as well as the traditional static licensed spectrum access (SLSA) technique as a baseline. In addition, we discuss the implementation perspectives of DSAS. With numerical and simulation studies on an arbitrary country with four MNOs, we evaluate and then compare the performances of both the proposed DSAS technique and the SLSA technique. It is shown that the DSAS technique can improve both the capacity and the SE by 204.78%, whereas the EE and the CE by 67.19%, over that of the SLSA technique. Finally, we show that, by applying the DSAS technique, the prospective requirements of SE and EE for sixth-generation (6G) networks can be achieved by reusing the 28-GHz spectrum to 64.86% fewer buildings of small cells than that required by the SLSA technique.

1. Introduction

1.1. Background. The ever-increasing demand for the large capacity and the scarcity of the available radio spectrum cause mobile operators to move toward the high-frequency millimeter-wave spectrum bands [1] as well as to utilize the available spectrum effectively [2]. Currently, spectrum management policy is seen as an effective strategical approach to realize the demand of user services depending on the available radio spectrum of a mobile communication system [3]. The increase in the available radio spectra and the capacity, as well as high data rate, demands of users of a mobile network operator (MNO), has not been in proportion over the past decades [4]. This causes the traditional static licensed spectrum allocation model to be no longer predominant as each MNO is allowed to operate only in its allocated licensed spectrum, typically, for a long time [3]. Such an exclusive right to use spectrum by each MNO in a country results in poor utilization in time, frequency, and space of the overall spectrum specified for the country. Hence, this asks for adopting a spectrum management policy that is more progressive, including features, for example, liberalization and flexibility [3, 5].

Liberalization defines the maximum level up to which spectrum usage rights can be managed through mechanisms, mainly addressing issues from competitive assignments (e.g., from the spectrum auction to the secondary spectrum trading) [5]. However, flexibility focuses on easing spectrum usage rights constraints [3], including spectrum commons (with equal rights to access the spectrum by everyone) and
managed shared-use model where an unlicensed user can access the spectrum of a licensed user dynamically subject to causing no interference to the licensed user [5, 6].

1.2. Related Work. Issues concerning the liberalization and flexibility of the spectrum have been addressed discretely in the existing literature by several research studies. For example, about the spectrum auction, an auction-based resource allocation scheme has been presented between a spectrum broker and base stations (BSs) in [7]. The authors in [8] have designed a spectrum double auction that incorporates locality in spectrum markets while keeping the auction economically robust and computationally efficient. In [9], the authors have proposed an auction-based spectrum leasing for hybrid access in a macro-femto network with location sensing to maximize the utilities of the macrocell BS and femto-cell access points. Moreover, in [10], the authors have proposed to model nonlicensed users as secondary networks and used simple examples to show that such auctions among secondary networks differ drastically from simple auctions among single-hop users, as well as previous solutions suffer from local, per-hop decision-making.

For spectrum trading, by exploiting the secondary spectrum trading (sharing partly and exclusively the spectrum of one MNO to another for a certain agreement term), a dynamic exclusive-use spectrum access technique has been proposed in [11]. Likewise, the authors in [12] have proposed a two-tier spectrum trading strategy, whereas in [13], a bandwidth-auction game for the spectrum trading problem of a cellular network has been introduced. Furthermore, in [14], the spectrum trading system has been studied from the service-oriented perspective, while in [15], the spectrum trading problems have been formulated by employing contract theory. Besides, in [16], a privacy-preserving secure spectrum trading and sharing scheme based on blockchain technology has been proposed between the aerial and terrestrial communication systems.

Regarding the shared-use case to address the spectrum flexibility, co-primary spectrum sharing (CoPSS) techniques have been presented in [17, 18]. Particularly, in [18], to overcome the constraints of conventional CoPSS techniques, the authors have proposed two CoPSS techniques for in-building small cells, namely, dynamic spectrum pooling (DySP) and static spectrum renting (StSR). In DySP, by exploiting the external wall penetration loss of a building and avoiding cochannel interference (CCI), the whole spectrum of one MNO can be shared only with small cells per building of the other MNO and vice versa, while in StSR, a portion of the spectrum of one MNO can be rented exclusively by another MNO without any pre-emptive priority of the owner MNO.

A licensed shared access method has been proposed in [19] to exploit intercell interference coordination of an MNO. Furthermore, the main concepts of dynamic spectrum sharing in [20] and the spectrum sharing approaches and user association mechanisms in [21] have been studied. Furthermore, in [22], numerous key spectrum management challenges have been discussed to overcome with a view to promoting dynamic spectrum sharing at the millimeter-wave (mmWave) spectrum bands. Besides, recently, the authors in [23] have introduced a new technique called licensed countrywide full-spectrum allocation (LCFSA) to allocate the licensed countrywide full 28-GHz mmWave spectrum to each MNO of a country to operate its small cells per building by avoiding CCI in both the time domain and frequency domain with a view to increasing the spectrum availability and utilization.

Likewise, concerning spectrum commons, the usefulness of the spectrum commons has been presented in [24], whereas implementation challenges associated with managing a spectrum common have been addressed in [25]. Furthermore, for the intertechnology coexistence in spectrum commons, the authors in [26] have studied the performance of different spectrum sharing schemes, whereas in the spectrum commons, the authors in [27] have demonstrated superior economics of collaborative production.

1.3. Problem Statement. As mentioned above, numerous approaches such as spectrum auction and spectrum trading for liberalizing and spectrum commons and shared-use models for assigning the spectrum flexibly have been considered in the existing literature. However, an approach that can address both spectrum liberalization and spectrum flexibility to take advantage of their closely interlinked feature for more progressive spectrum management policies to provide more efficient spectrum utilization is not yet obvious. In this regard, a two-level dynamic spectrum allocation and sharing approach can be considered such that the spectrum liberalization can be exploited in the primary-level dynamic spectrum allocation, whereas the spectrum flexibility can be exploited in the secondary-level spectrum sharing dynamically.

Furthermore, most mobile data are generated in indoor environments, noticeably, in urban multistory buildings. In this regard, good channel conditions of mmWave signals in indoor environments result in operating small cells deployed in buildings on mmWave bands, which is considered an effective technique to address high capacity and data rate demands in indoor environments for the next-generation cellular systems.

In line with so, by exploiting either time, frequency, or power domain, recently, numerous researches have addressed the dynamic spectrum access issue. For example, in [28], the authors have proposed a power domain-based dynamic spectrum access technique by controlling the transmission power of in-building small cells of any MNO in a country considering that each MNO is allocated to an equal amount of the 28-GHz spectrum. Similarly, by exploiting the power domain, the authors in [29] have proposed a technique to share dynamically the whole countrywide 28-GHz spectrum to small cells of each MNO in a country subject to satisfying the maximum cochannel interference limit experienced from a small cell of one MNO to a small cell of another within each apartment of a building. Unlike [28], the whole countrywide spectrum has been considered available...
to each MNO resulting in avoiding the spectrum allocation at the primary level.

Furthermore, unlike [28, 29], the authors have proposed a dynamic spectrum access technique to get access to the whole countrywide spectrum by small cells of each MNO by applying the time domain in [21] and the frequency domain in [30] CCI interference avoidance technique among small cells of different MNOs when attempting to get access to the whole 28-GHz spectrum. Like [29], no primary-level spectrum allocation among MNOs countrywide has been considered in [21, 30] as well.

Therefore, a primary-level dynamic spectrum allocation to all MNOs in a country, which liberalizes the allocation of the licensed 28-GHz spectrum, can help gain high 28-GHz spectrum utilization countrywide. Similarly, the secondary-level dynamic spectrum sharing can allow sharing dynamically the unused licensed mmWave spectrum of one MNO, termed as primary MNO (p-MNO), with small cells in a building of another MNO, termed as secondary MNO (s-MNO), to exploit the mmWave spectrum of the p-MNO in order to address the demands of high capacity and data rates of s-MNO users within the building.

1.4. Novelty and Contribution. Unlike the existing spectrum management approaches given above, a two-level dynamic spectrum allocation and sharing (DSAS) technique (addressing both spectrum liberalization and spectrum flexibility for more progressive spectrum management) is proposed in this article to improve the 28-GHz spectrum utilization countrywide. More specifically, to liberalize allocating countrywide spectrum to MNOs, in the primary level, an MNO is allocated to the 28-GHz spectrum in proportionate to its number of subscribers for a certain term, whereas to exploit spectrum flexibility in the secondary level, any p-MNO’s allocated spectrum in the primary level can be allowed to share with small cells in a building of any s-MNO when no user equipment (UE) of the p-MNO is present inside the building to avoid CCI.

An abstract view of how the spectrum liberalization, as well as spectrum flexibility, of the proposed DSAS technique, is obtained, considering level 2 spectrum sharing for MNO 2, for example, is shown in Figure 1 at any renewal term. We will discuss the proposed technique in detail in a later section.

Furthermore, the following are the contributions of this article as well:

(i) The licensed mmWave spectrum in the primary-level spectrum allocation for each MNO in a country is defined.

(ii) Based on the licensed mmWave spectrum allocated to all MNOs in the primary-level spectrum allocation, we then estimate the amount of shared spectrum for in-building UEs of each MNO in the secondary-level spectrum sharing.

(iii) We derive and compare numerous performance metrics in terms of system-level average capacity, spectral efficiency (SE), energy efficiency (EE), and cost efficiency (CE) for the proposed DSAS and the traditional static licensed spectrum access (SLSA) (where each MNO in a country is allocated to an equal amount of spectrum exclusively) techniques. Furthermore, the implementation perspectives of the proposed DSAS are discussed.

(iv) With numerical and simulation studies on an arbitrary country with four MNOs, the overall countrywide performance improvements in terms of the above metrics of DSAS over that of SLSA are shown and compared.

(v) Finally, it is shown that DSAS can gain the expected SE and EE requirements for sixth-generation (6G) mobile networks.

1.5. Organization. We organize the article as follows. The system architecture and the DSAS technique are presented in Section 2. The proposed DSAS technique is then analyzed mathematically in Section 3. In Section 4, the relevant performance metrics for the DSAS and SLSA techniques are derived. Section 5 covers parameters and assumptions for the simulation, along with performance evaluation results, analyses, and comparisons of the DSAS technique. The article is concluded in Section 6. A list of abbreviations is given in Table 1.

1.6. Declaration. Note that some of the materials of this article may be found similar or merged with our previous works, notably [4, 5, 28, 29] and [31], in terms of texts, notations, abbreviations, equations, figures, and tables. However, the scope of problems, proposed contributions, key features, novelty, and technical contents of this article with those mentioned above are different. To demonstrate the position of this article with respect to these aforementioned works, a comparison of these existing works with this article is given in Table 2 with relevant discussions as follows.

From Table 2, it can be found that, among all, the scope of [5] merges mostly with the scope of this article. However, if we observe closely, it can be found that this article is an extended version of the conference paper [5], which was written by the same authors as that of this article. In fact, our preliminary study was reported in [5], which was later extended extensively by relaxing the assumptions considered in [5], including extending the mathematical analysis using Pascal’s triangle and equal likely criterion in detail from a limited number of MNOs (i.e., four) considered in [5] to an arbitrary number of MNOs in a country. Secondly, we extend the scope of [5] toward addressing the dynamic sharing in level 2 of the spectrum allocated to an arbitrary number of MNOs in level 1 (in fact, the scope of [5] is limited by level 1 only). Thirdly, unlike [5], we discuss the implementation of the proposed technique DSAS in this article.

When compared to other works in Table 2, particularly [4, 28, 29] are mainly based on the cognitive radio principle that exploits the transmission power of in-building small cell base stations. Moreover, references [5, 28] assume that each MNO is allocated statically to an equal amount of mmWave
TABLE 1: A list of abbreviations.

| Abbreviation | Explanation |
|--------------|-------------|
| 3D           | Three-dimensional |
| 3GPP         | Third-generation partnership project |
| 5G           | Fifth-generation |
| 6G           | Sixth-generation |
| BS           | Base station |
| CCI          | Cochannel interference |
| CE           | Cost efficiency |
| CP           | Average capacity |
| CSG          | Closed subscriber group |
| CSI          | Channel state information |
| DSAS         | Dynamic spectrum allocation and sharing |
| EE           | Energy efficiency |
| ITU-R        | International telecommunication union-radiocommunication |
| MBS          | Macrocell base station |
| mmWave       | Millimeter-wave |
| MNO          | Mobile network operator |
| NRA          | National regulatory agency |
| PBS          | Picocell base station |
| PF           | Proportional fair |
| p-MNO        | Primary mobile network operator |
| PSA          | Primary spectrum allocation |
| RB           | Resource block |
| SBS          | Small cell base station |
| SE           | Spectral efficiency |
| SLSA         | Static licensed spectrum access |
| SSS          | Secondary mobile network operator |
| s-MNO        | Secondary spectrum sharing |
| TTI          | Transmission time interval |
| UE           | User equipment |
Table 2: A comparison of this article with relevant existing works.

| Reference | Description |
|-----------|-------------|
| [4]       | An interweave strategy-based shared-use model to share the licensed 28-GHz mmWave spectrum of one MNO with another in a country. The paper emphasizes the following: (i) Policy for spectrum allocation to each MNO: static and equal; a portion of the countrywide full spectrum (ii) Major spectrum management strategy: spectrum sharing between p-MNO and s-MNO is possible only if no UE of the p-MNO is present inside the same building to avoid CCI (iii) Exploited domain for CCI avoidance: time (iv) Number of levels exploited for the dynamic allocation and sharing of the spectrum: one level (v) Number of MNOs assumed: limited (i.e., four) (vi) Type of paper: research article (conference) A flexible licensed spectrum allocation technique to liberalize allocating the licensed 28-GHz mmWave spectrum to MNOs of a country. The paper emphasizes the following: (i) Policy for spectrum allocation to each MNO: flexible and unequal; the spectrum is allocated to an MNO in accordance with its number of subscribers (ii) Major spectrum management strategy: spectrum allocation (iii) Exploited domain for CCI avoidance: frequency (iv) Number of levels exploited for the dynamic allocation and sharing of the spectrum: one level (v) Number of MNOs assumed: limited (i.e., four) (vi) Type of paper: research article (conference) A hybrid interweave-underlay spectrum access and reuse technique for the dynamic spectrum access and reuse of the countrywide full 28-GHz mmWave spectrum to each MNO in the country. The following is highlighted in the paper: (i) Policy for spectrum allocation to each MNO: spectrum access by each MNO to the countrywide full 28 GHz is subjected to operating an MNO in the interweave mode if no UE of other MNOs is present, whereas in the underlay mode if a UE of any interfering-MNO is present within the same apartment of a building (ii) Major spectrum management strategy: spectrum allocation and spectrum reuse (iii) Exploited domain for CCI avoidance: power (iv) Number of levels exploited for the dynamic allocation and sharing of the spectrum: one level (v) Number of MNOs assumed: limited (i.e., four) (vi) Type of paper: research article (journal) Power-domain-based dynamic spectrum access and reuse techniques for sharing the 28-GHz spectrum of one MNO with another by exploring both the interweave and underlay access techniques for an arbitrary number of MNOs in a country. The authors address the following in the paper: (i) Policy for spectrum allocation to each MNO: static and equal; a portion of the countrywide full spectrum (ii) Major spectrum management strategy: spectrum sharing and spectrum reuse (iii) Exploited domain for CCI avoidance: power (iv) Number of levels exploited for the dynamic allocation and sharing of the spectrum: one level (v) Number of MNOs assumed: arbitrary (vi) Type of paper: research article (journal) A framework to give a comprehensive review of how to improve the spectrum utilization of mmWave systems using indoor small cells in multioperator network scenarios. The authors discuss the following in the paper: (i) Policy for spectrum allocation to each MNO: static and equal, flexible and unequal, as well as, countrywide full spectrum (ii) Major spectrum management strategy: spectrum allocation, spectrum trading, spectrum sharing, and spectrum reusing (iii) Exploited domain for CCI avoidance: time, frequency, power, and space (iv) Number of levels exploited for the dynamic allocation and sharing of the spectrum: two levels: level 1 for spectrum allocation (both static and dynamic) and level 2 for spectrum trading, sharing, and reusing (v) Number of MNOs assumed: arbitrary (vi) Type of paper: review article (journal) A two-level dynamic spectrum allocation and sharing (DSAS) technique is proposed to improve the countrywide spectrum utilization of the 28-GHz mmWave for an arbitrary number of MNOs. In level 1, each MNO is assigned with an amount of 28-GHz spectrum corresponding to its number of subscribers for a certain spectrum renewal term, whereas, in level 2, the allocated spectrum to an MNO in level 1 is allowed to share with small cells of another MNO in a building. The paper emphasizes the following: (i) Policy for spectrum allocation to each MNO: flexible and unequal; the spectrum is allocated to an MNO in accordance with its number of subscribers (ii) Major spectrum management strategy: spectrum allocation in level 1 and spectrum sharing in level 2 between p-MNO and s-MNO is possible only if no UE of the p-MNO is present inside the same building to avoid CCI (iii) Exploited domain for CCI avoidance: frequency (iv) Number of levels exploited for the dynamic allocation and sharing of the spectrum: two levels: level 1 for spectrum allocation (only dynamic) and level 2 for spectrum sharing (v) Number of MNOs assumed: arbitrary (vi) Type of paper: research article (journal)
spectrum, whereas [29] assumes that each MNO can be allocated to the countrywide full mmWave spectrum subject to CCI avoidance. Unlike these works, in this article, we consider that each MNO is allocated to an amount of spectrum in proportion to its number of subscribers in any term to improve spectrum utilization. We show clearly the effectiveness of the proposed technique with an example scenario in this article.

Finally, with regard to [31], the basic difference is that [31] is a review paper, unlike this research article. In fact, in [31], we provide a comprehensive review of our recent numerous works on dynamic spectrum sharing, including this article. Unlike [31], our goal in this article is to give detailed modeling and analysis on the proposed technique, which we simply referred to in [31] like our other published papers. Hence, there is, basically, no clear way to compare this article with [31]. This article was in fact under preparation, while [31] was published and is just a review part of [31] that we used in it for completeness. In short, we propose and detail the two-level dynamic spectrum allocation and sharing technique in this article that we referred to in [31].

2. System Architecture and Proposed Technique

2.1. System Architecture. We consider a system model that consists of O MNOs in a country. Following [29], we also assume that each MNO in a country has a similar system architecture such that the system architecture of only one (i.e., MNO 1) of four MNOs (namely, MNO 1, MNO 2, MNO 3, and MNO 4), for example, in a country, is shown broadly in Figure 2(a). Picocell BSs (PBSs) in outdoor environments serve to offload some of the traffic of the macrocell BS (MBS). All small cell BSs (SBSs) are deployed in 3-dimensional (3D) multistory buildings, and each SBS serves one UE at a time. A proportional fair (PF) scheduler per building schedules resource blocks (RBs) to small cell UEs deployed within the building. All SBSs operate at the 28-GHz mmWave wave, whereas all BSs, including the MBS and PBSs, operate at the 2-GHz microwave band [11, 23].

Consider that a dedicated licensed mmWave spectrum is allocated to each MNO, which may vary from that of other MNOs countrywide as shown by the level 1 spectrum allocation in Figure 2(b). Moreover, since the use of the licensed spectrum of one MNO differs from another in time, frequency, and space, an MNO may share opportunistically its spectrum with indoor small cells of another [4] as shown by the level 2 spectrum sharing in Figure 2(b) as long as no CCI would occur between UEs of both MNOs. Both level 1 spectrum allocation and level 2 spectrum sharing constitute the DSAS technique that we propose and discuss in detail in the following section.

2.2. Proposed Technique. A two-level dynamic spectrum allocation and sharing (DSAS) technique for the countrywide licensed 28-GHz mmWave spectrum to improve its utilization is proposed as follows. Level 1 concerns the dynamic spectrum allocation, whereas level 2 concerns dynamic spectrum sharing, stated as follows.

"In primary (i.e., level 1) spectrum allocation (PSA), each MNO is allocated to a licensed 28-GHz spectrum of a country in accordance with its number of subscribers for a certain renewal term. In secondary (i.e., level 2) spectrum sharing (SSS), the licensed mmWave spectrum in PSA of an MNO, termed as p-MNO, can be shared with in-building small cells of any other MNOs, termed as s-MNO, only if no UE of the p-MNO is present inside the building to avoid CCI between UEs of the p-MNO and s-MNO. Otherwise, no spectrum of the p-MNO can be shared with the s-MNO. The licensed mmWave spectrum in PSA of each MNO is updated at each renewal term compliant with its change in the number of subscribers such that the sum of the updated spectra of all MNOs in PSA is equal to the countrywide 28-GHz spectrum."

In this regard, we assume that the national regulatory agency (NRA) in a country is responsible to manage spectrum sharing among numerous MNOs in the system. Moreover, by sensing the spectrum usage of each p-MNO continuously within a building, an s-MNO can identify the unused spectrum of any p-MNO [5] and switch back and forth from using the shared spectrum of the p-MNO with minimal coordination. In this regard, an s-MNO may apply either reactive or proactive spectrum sensing approaches to detect the shared spectrum usage of any p-MNO. In the reactive approach, by carrying out the spectrum sensing mechanism, an s-MNO itself can detect the shared spectrum usage. However, in the proactive approach, an s-MNO predicts beforehand the arrival of UEs of a p-MNO using their traffic mode [29, 32].

Overall, unlike SLSA, by allocating spectrum to an MNO in proportionate to its user demand, DSAS in the PSA addresses the issues of the scarcity of the allocated spectrum of one p-MNO and the unused or underutilization of the allocated spectrum of another p-MNO in a country. Furthermore, the proposed technique allows an s-MNO to share with the licensed spectrum of a p-MNO opportunistically in SSS to gain additional capacity, resulting in improving the overall countrywide spectrum utilization.

Besides, it allows a p-MNO to pay only the fee of its required licensed spectrum in PSA, and an s-MNO to pay nothing for the shared spectrum in SSS, resulting in improving the overall countrywide cost efficiency. More specifically, an s-MNO can share the spectrum of a p-MNO only when no UE of p-MNO exists, that is, when the spectrum of p-MNO is idle. Due to this reason, no performance degradation of p-MNO is resulted from sharing its spectrum with any s-MNO. Because each MNO can share the licensed spectrum of another MNO to increase its available spectrum without hampering its performance, it is fairly practical enough to consider that no MNO needs to pay for its shared spectrum of other MNOs, resulting in improving the cost efficiency. A noticeable characteristic of DSAS is that it gets benefited from improving the utilization of the overall spectrum
specified for a country by liberalizing the spectrum in PSA unlike market-based approaches such as auction and spectrum trading in SSS [3].

3. Mathematical Analysis of DSAS

3.1. PSA in DSAS. In PSA, assume that there are $O$ MNOs in a country such that $o \in O$: $O = \{1, 2, \ldots, O\}$. Let $t_{\text{raw}}$ denote the licensed spectrum renewal term of any MNO $o$. Denote $N_{o,t_{\text{raw}}}$ as the number of subscribers of an MNO $o$ such that $N_{o,t_{\text{raw}}} > 0$ and $N_{\text{C, max}, t_{\text{raw}}}$ as the countrywide maximum number of subscribers of all MNOs $O$ at any term $t_{\text{raw}}$. Because the number of subscribers of one MNO differs from another at any $t_{\text{raw}}$, we assume that $N_{1,t_{\text{raw}}} > N_{2,t_{\text{raw}}} > \cdots > N_{O,t_{\text{raw}}}$ such that $\sum_{o=1}^{O} N_{o,t_{\text{raw}}} = N_{\text{C, max}, t_{\text{raw}}}$.

Likewise, let $M_{o,t_{\text{raw}}}$ be the 28-GHz spectrum in RBs allocated to an MNO $o$ and $M_{\text{C, max}}$ be the countrywide 28-GHz spectrum in RBs at any $t_{\text{raw}}$ such that $\sum_{o=1}^{O} M_{o,t_{\text{raw}}} = M_{\text{C, max}}$ where an RB is equal to 180 kHz. Now, to satisfy the condition of the proposed DSAS technique, since $N_{o,t_{\text{raw}}} > 0$, $M_{o,t_{\text{raw}}} > 0$ must hold. Then, the optimal value of $M_{o,t_{\text{raw}}}$ in RBs needed to serve $N_{o,t_{\text{raw}}}$ for an MNO $o \in O$ at any $t_{\text{raw}}$ can be expressed as follows:

$$M_{o,t_{\text{raw}}} = \frac{N_{o,t_{\text{raw}}} \times M_{\text{C, max}}}{N_{\text{C, max}, t_{\text{raw}}}}$$

(1)

$$M_{o,t_{\text{raw}}} = \frac{N_{o,t_{\text{raw}}} \times \sum_{o=1}^{O} M_{o,t_{\text{raw}}}}{\sum_{o=1}^{O} N_{o,t_{\text{raw}}}}$$

(2)

Hence, using (2), the 28-GHz mmWave spectrum allocated to each MNO $o$ at any $t_{\text{raw}}$ can be updated flexibly and on-demand basis to address its user demands in PSA.

3.2. SSS in DSAS. Consider that a small cell of each MNO is deployed in each apartment of a building. Besides, following [33], we also adopt that each SBS serves only one UE at a time. Certainly, in practice, the UE density per SBS can be more than one. However, such simplifications in the assumptions are reasonable for the system-level performance evaluation, which is clarified in Remark 1.

Remark 1. Spectrum RBs are allocated orthogonally to small cell UEs of an MNO $o$ in a building at any transmission time interval (TTI) by a PF scheduler based on the channel
conditions of all small cell UEs of MNO $o$. Due to this reason, an increase in the user density of any SBS (e.g., SBS A) may cause to schedule some of the RBs allocated already to UEs of its other SBSs of MNO $o$ back to the new UEs of SBS A by the scheduler. Such a change in the user density of SBS A does not change noticeably the overall system-level capacity of MNO $o$. This is because if there were no increase in the user density of SBS A, no additional RB would be scheduled back to SBS A to serve its new UEs such that there would be no increase in the capacity of SBS A and a corresponding decrease in the capacity of other SBSs of MNO $o$. This results in no considerable change in the overall system-level capacity of MNO $o$. That’s why, instead of multiple UEs per SBS, the proposed technique is investigated for a single UE per SBS for deriving closed-form expressions and simplicity in the analysis [31].

Hence, following the above assumption, a maximum number of $O$ UEs one per MNO could present at any TTI per apartment. The existence of a UE of an MNO $o$ in an apartment can be represented by binary digits. More specifically, assume that the binary digit 1 denotes the presence, whereas the binary digit 0 denotes the absence of a UE of an MNO $o$ in an apartment such that there are $2^O$ possible ways $O$ UEs can coexist in an apartment. For simplicity in analysis, we assume that each possible way of coexistence in the above is equally likely such that for the presence of a UE of any MNO $o$ (i.e., s-MNO) in an apartment, which corresponds to the binary digit 1, UEs of other MNOs $O_o$ (i.e., p-MNOs) can coexist in $2^{O-1}$ ways, each occurring at a probability of $(1/2^{O-1})$ and lasting for $(Q/2^{O-1})$ during time $Q$.

Now, based on the above findings, for any $O$, we can define the amount of the shared spectrum for a UE of any MNO $o$ given the presence of UEs of other MNOs $O_o$ in a country. For example, using Figure 2 for $O=4$, the maximum possible combinations that a UE $u_t$ of MNO 1 as an s-MNO can coexist with other UEs $u_t$, $u_3$, and $u_t$ of MNOs 2, 3, and 4, respectively, as p-MNOs are $\{u_t\}$, $\{u_1, u_t\}$, $\{u_1, u_3\}$, $\{u_1, u_4\}$, $\{u_1, u_3, u_4\}$, $\{u_1, u_2, u_3\}$, $\{u_1, u_3, u_4\}$, and $\{u_1, u_2, u_3, u_4\}$ where each occurs with a probability of $(1/2^{4-1})$ in an apartment. Recall that $M_{C, max} = M_{1, traw} + M_{2, traw} + M_{1, traw} + M_{4, traw}$ at $t_{raw}$. Then, each of the above possible combinations in an apartment corresponds to the shared spectrum (as given in column 5) and the total spectrum (as given in column 6) of Table 3 for $u_t$. For simplicity, we denote $(M_{1, traw} + M_{2, traw} + M_{3, traw} + M_{4, traw})$ as $M_{1,2,3,4, traw}$ (i.e., the sum of spectra in RBs of MNOs defined by the corresponding numerical subscripts). Likewise, all other summations are denoted in column 6 of Table 3. Sheet1

Note that, in practice, because of huge investment and tough competition in the market, $O$ is a small positive integer, typically ranging from 3 [34] to 5 [35, 36]) in the market of most of the countries in the world. Therefore, Table 3 is not computationally exhaustive, and hence, in line with so, we consider an average value of $O = 4$ in a country to show the formation of Table 3 in SSS. As in Table 3 for $O = 4$, we can define the spectrum in SSS for any UE of MNO $o$ in each apartment of a building for any arbitrary number of MNOs $O$ in a country.

Nevertheless, when all MNOs $O$ in a country is allocated to a different amount of spectrum from each other in PSA, a major concern with the above approach to developing Table 3 is that the shared spectrum for a UE in SSS (in Table 3) changes with a change in $O$. This cause to develop Table 3 further as $O$ changes such that generic expressions for the system-level performance metrics of all MNOs $O$ are difficult to formulate. However, for allocating an equal amount of spectrum to each MNO, a generic approach for the formation of Table 3 can be established following Theorem 1 such that relevant generic expressions for the system-level performance metrics of an arbitrary number of MNOs $O$ can be formulated.

**Theorem 1.** The formation of Table 3 in SSS follows a left-justified Pascal’s triangle if each MNO $o \in O$: $O = \{1, 2, \ldots, O\}$ is allocated to an equal amount of spectrum in a country.

**Proof.** Proof 1 is given in the Appendix.

**Theorem 2.** The total amount of the spectrum of all MNOs $O$ in a country due to applying the SSS does not change irrespective of each MNO $o$ is allocated whether to an equal amount of spectrum or an unequal amount of spectrum, causing no change in the results of the system-level performance metrics of all MNOs $O$ each allocated to a spectrum different from that of the other countrywide.

**Proof.** Proof 2 is given in the Appendix.

Hence, following Theorem 2 and using Table 4, alternatively, by considering in the SSS that an equal amount of spectrum is allocated to each MNO $o$, we can find relevant generic expressions for the system-level performance metrics of all MNOs $O$ each allocated to a spectrum different from that of the other countrywide.

4. Performance Metrics Estimation

4.1. Preliminary. Assume that there is an $L$ number of buildings of small cells over the coverage of a macrocell of each MNO such that $l \in \{1, 2, \ldots, L\}$. Let $S_{p}$ denote the number of small cells deployed in each of the $L$ buildings such that $s \in \{1, 2, \ldots, S_{p}\}$. Denote $S_{M}$ and $S_{p}$ as the number of MBSSs per MNO and PBSs per MBS, respectively. Let $T = \{1, 2, 3, \ldots, Q\}$ denote the simulation run time with the maximum time of $Q$ (in time step each lasting 1 ms). Also, let $P_{MC}$, $P_{PC}$, and $P_{SC}$ denote the transmission power of an MBS, a PBS, and an SBS of any MNO, respectively.

Let $\beta$ denote the implementation loss factor. Then, for an MNO $o$ at $t_{raw}$, a link throughput at $RB = i$ in TTI $= t$ in bps per Hz can be given by using Shannon’s capacity formula as follows:
respectively, as follows:

\[ M_{t,rnw} = (M_{2,2,2,2} + M_{3,2,2,2} + M_{4,2,2,2}) \]

\[ M_{1,2,3,4,rnw} = (M_{1,2,2,2} + M_{2,2,3,2} + M_{4,2,3,2}) \]

\[ M_{1,2,3,4,rnw} = (M_{1,2,2,2} + M_{2,2,3,2} + M_{4,2,3,2}) \]

\[ M_{1,2,3,4,rnw} = (M_{1,2,2,2} + M_{2,2,3,2} + M_{4,2,3,2}) \]

Not applicable due to nonexistence of \( u_i \)

| \( u_1 \) | \( u_2 \) | \( u_3 \) | \( u_4 \) | Shared | Spectrum for \( u_1 \) |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | | |
| 0 | 0 | 0 | 1 | | |
| 0 | 0 | 1 | 0 | | |
| 0 | 0 | 1 | 1 | | |
| 0 | 1 | 0 | 0 | | |
| 0 | 1 | 0 | 1 | | |
| 0 | 1 | 1 | 0 | | |
| 0 | 1 | 1 | 1 | | |
| 1 | 0 | 0 | 0 | | |
| 1 | 0 | 0 | 1 | | |
| 1 | 0 | 1 | 0 | | |
| 1 | 0 | 1 | 1 | | |
| 1 | 1 | 0 | 0 | | |
| 1 | 1 | 0 | 1 | | |
| 1 | 1 | 1 | 0 | | |
| 1 | 1 | 1 | 1 | | |

**Table 3:** Coexistence and shared spectrum for \( u_1 \) of MNO 1 in SSS of the proposed DSAS for \( O = 4 \).

**Table 4:** Multipliers of the components of the shared spectrum for \( u_1 \) of MNO 1 in SSS when the same amount of spectrum \( M \) is allocated to each MNO for any number of MNOS \( O \) in a country.

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

\[
s_{t,rw}^{i,t,SLSA} = \sum_{t \in T} \sum_{i=1}^{M} s_{t,i,0}^{t,rw}(\rho_{1,1,0}^{t,rw}), \quad s_{t,i,0}^{t,rw,SLSA} = \sum_{t \in T} \sum_{i=1}^{M} s_{t,rw}^{i,t,SLSA}
\]  

Denote \( M_{MBS,o} \) as the 2-GHz microwave spectrum of an MBS for \( o \). Then, following [11, 29], the aggregate capacity for an MNO \( o \) and for all MNOs \( O \) at \( t_{rnw} \) can be expressed, respectively, as follows:

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

\[
\sigma_{t,rw}^{i,t} = \sum_{t \in T} \sum_{i=1}^{M} s_{t,i,0}^{t,rw}(\rho_{1,1,0}^{t,rw}), \quad \sigma_{t,rw}^{i,t,SLSA} = \sum_{t \in T} \sum_{i=1}^{M} s_{t,i,0}^{t,rw,SLSA}
\]  

4.2. Traditional SLSA. In the traditional SLSA, each MNO \( o \) is allocated to a spectrum of \( M \) RBs (i.e., \( \forall oM_{t,rnw} = M \) at term \( t_{rnw} \)). Then, for all SBSs in a building serving simultaneously in \( t \in T \), the aggregate capacity of an SBS and all SBSs of an MNO \( o \) per building due to applying SLSA can be given by, respectively,

\[
\sigma_{t,rw}^{i,t,SLSA} = \sum_{t \in T} \sum_{i=1}^{M} s_{t,i,0}^{t,rw}(\rho_{1,1,0}^{t,rw}), \quad \sigma_{t,i,0}^{t,rw,SLSA} = \sum_{t \in T} \sum_{i=1}^{M} s_{t,i,0}^{t,rw,SLSA}
\]  

We assume similar indoor signal propagation characteristics for all \( L \) buildings per macrocell for an MNO \( o \) at \( t_{rnw} \) due to a short distance between an SBS and its serving UE, as well as the low transmission power of an SBS. Then, by linear approximation, the system-level average aggregate capacity in bps, SE in bps/Hz, and EE in Joule/bit due to applying the SLSA technique for \( O \) MNOs countrywide at \( t_{rnw} \) can be expressed as follows, respectively:
4.3. Primary Spectrum Allocation. Now, if we consider applying the PSA such that \( N_{1_{_{\text{raw}}}} > N_{2_{_{\text{raw}}}} > \cdots > N_{\text{O}_{_{\text{raw}}}} \) at \( t_{\text{raw}} \), then \( M_{1_{_{\text{raw}}}} > M_{2_{_{\text{raw}}}} > \cdots > M_{\text{O}_{_{\text{raw}}}} \) subject to \( \sum_{o=1}^{O} M_{o_{_{\text{raw}}}} \leq M_{\text{C, max}} \). Hence, the system-level average aggregate capacity, SE, and EE for O MNOs in a country at \( t_{\text{raw}} \) due to applying the PSA are given as follows for \( L > 1 \), respectively:

\[
\begin{align*}
\sigma_{\text{cap, O, PSA}}^{\text{mmW}_{\text{raw}}} (L) &= \sum_{o=1}^{O} \left( \sigma_{\text{mmW}_{\text{raw}}}^{\text{MBS, o}} + L \times \sigma_{\text{mmW}_{\text{raw}}}^{\text{SLSA, o}} \right), \\
\sigma_{\text{SE, O, PSA}}^{\text{mmW}_{\text{raw}}} (L) &= \frac{\sigma_{\text{cap, O, PSA}}^{\text{mmW}_{\text{raw}}} (L)}{\left( \sum_{o=1}^{O} M_{\text{MBS, o}} + (O \times M) \times Q \right)}, \\
\sigma_{\text{EE, O, PSA}}^{\text{mmW}_{\text{raw}}} (L) &= \frac{O \times \left( (L \times S_{P} \times P_{PC}) + (S_{M} \times P_{MC}) \right)}{\left( \sigma_{\text{cap, O, PSA}}^{\text{mmW}_{\text{raw}}} (L)/Q \right)}.
\end{align*}
\]

Therefore, the average capacity, SE, and EE improvement factors because of applying the PSA can be given for O MNOs at term \( t_{\text{raw}} \) by, respectively,

\[
\begin{align*}
\frac{\sigma_{\text{cap, O, PSA}}^{\text{mmW}_{\text{raw}}}}{\sigma_{\text{cap, O, SLSA}}^{\text{mmW}_{\text{raw}}}} &= \frac{\sigma_{\text{cap, O, PSA}}^{\text{mmW}_{\text{raw}}} (L)}{\sigma_{\text{cap, O, SLSA}}^{\text{mmW}_{\text{raw}}} (L)}, \\
\frac{\sigma_{\text{SE, O, PSA}}^{\text{mmW}_{\text{raw}}}}{\sigma_{\text{SE, O, SLSA}}^{\text{mmW}_{\text{raw}}}} &= \frac{\sigma_{\text{SE, O, PSA}}^{\text{mmW}_{\text{raw}}} (L)}{\sigma_{\text{SE, O, SLSA}}^{\text{mmW}_{\text{raw}}} (L)}, \\
\frac{\sigma_{\text{EE, O, PSA}}^{\text{mmW}_{\text{raw}}}}{\sigma_{\text{EE, O, SLSA}}^{\text{mmW}_{\text{raw}}}} &= \frac{\sigma_{\text{EE, O, PSA}}^{\text{mmW}_{\text{raw}}} (L)}{\sigma_{\text{EE, O, SLSA}}^{\text{mmW}_{\text{raw}}} (L)}.
\end{align*}
\]

4.4. Proposed DSAS. Assume that SBSs in each building serve concurrently in \( t_{\text{raw}} \) such that using Table 4 for any values of \( O \), the aggregate capacity served by an SBS of any MNO \( o \) at \( t_{\text{raw}} \) due to applying the SSS is given by (17):

\[
\sigma_{s, o_{_{\text{SSS}}}}^{t_{\text{raw}}} = \sum_{i=1}^{Q/2^{2-1}} \sum_{j=1}^{M} \sum_{\mathbf{k}=1}^{O-1} \left( \sigma_{l, j, o_{_{\text{SSS}}}}^{k_{l, j, o_{_{\text{SSS}}}}} \right),
\]

Like SLSA, by linear approximation due to considering a similar indoor signal propagation characteristic for all \( L \) buildings, the system-level average aggregate capacity, SE, and EE when applying the proposed DSAS technique for all MNOs \( O \) countrywide at \( t_{\text{raw}} \) are given, respectively, as follows:

\[
\sigma_{\text{cap, O, SSS}}^{\text{mmW}_{\text{raw}}} (L) = \sum_{o=1}^{O} \left( \sigma_{\text{mmW}_{\text{raw}}}^{\text{SLSA, o}} \right),
\]

\[
\sigma_{\text{SE, O, SSS}}^{\text{mmW}_{\text{raw}}} (L) = \frac{\sigma_{\text{cap, O, SSS}}^{\text{mmW}_{\text{raw}}} (L)}{\left( \sum_{o=1}^{O} M_{\text{MBS, o}} + (O \times M) \times Q \right)},
\]

\[
\sigma_{\text{EE, O, SSS}}^{\text{mmW}_{\text{raw}}} (L) = \frac{O \times \left( (L \times S_{P} \times P_{PC}) + (S_{M} \times P_{MC}) \right)}{\left( \sigma_{\text{cap, O, SSS}}^{\text{mmW}_{\text{raw}}} (L)/Q \right)}.
\]
Hence, the average capacity, SE, and EE improvement factors at term $t_{\text{row}}$ for DSAS can be given as follows, respectively:

\[
\sigma_{\text{cap,DSAS}}^{\text{mmW},t_{\text{row}}} (L) = \frac{\sigma_{\text{cap,O,DSAS}}^{\text{mmW},t_{\text{row}}} (L)}{\sigma_{\text{cap,O,proposed}}^{\text{mmW}} (L)},
\]

\[
\sigma_{\text{SE,DSAS}}^{\text{mmW},t_{\text{row}}} (L) = \frac{\sigma_{\text{SE,O,DSAS}}^{\text{mmW},t_{\text{row}}} (L)}{\sigma_{\text{SE,O,proposed}}^{\text{mmW}} (L)},
\]

\[
\sigma_{\text{EE,DSAS}}^{\text{mmW},t_{\text{row}}} (L) = \frac{\sigma_{\text{EE,O,DSAS}}^{\text{mmW},t_{\text{row}}} (L)}{\sigma_{\text{EE,O,proposed}}^{\text{mmW}} (L)}.
\]

\[
\sigma_{\text{cap,DSAS}}^{\text{mmW},t_{\text{row}}} (L) = \sum_{o=1}^{D} \left( \sigma_{\text{MBS,O,DSAS}}^{\text{mmW},t_{\text{row}}} (L) \times \left( L \times \sigma_{\text{SSS,O,proposed}}^{\text{mmW}} \right) \right),
\]

\[
\sigma_{\text{SE,DSAS}}^{\text{mmW},t_{\text{row}}} (L) = \left( \sum_{o=1}^{D} \left( M_{\text{MBS,O,DSAS}}^{t_{\text{row}}} + M_{\text{MBS,O,proposed}}^{t_{\text{row}}} \right) \times Q \right),
\]

\[
\sigma_{\text{EE,DSAS}}^{\text{mmW},t_{\text{row}}} (L) = \left( O \times \left( L \times S_{\text{PC}} + (S_{\text{PC}} + P_{\text{MC}}) \right) \right) \left( \sigma_{\text{cap,O,proposed}}^{\text{mmW}} (L)/Q \right).
\]

4.5. Cost Efficiency. Let $\xi_C$ and $\xi_o$ denote the cost of the countrywide spectrum $M_{C,\text{max}}$ and the licensed spectrum $M_{o,\text{licensed}}$ of an MNO $o$ at term $t_{\text{row}}$, respectively, such that $\xi_C = \sum_{o=1}^{D} \xi_o$. We define cost efficiency as the cost required to achieve per unit average capacity, that is, per bits per second (bps). Like average capacity, SE, and EE, the CE due to applying SLSA, PSA, and DSAS at $t_{\text{row}}$ can be expressed as follows, respectively:

\[
\eta_{\text{CE,O,SLSA}}^{\text{mmW},t_{\text{row}}} (L) = \frac{\eta_{\text{CE,O,proposed}}^{\text{mmW},t_{\text{row}}} (L)}{\eta_{\text{CE,O,proposed}}^{\text{mmW}} (L)},
\]

\[
\eta_{\text{CE,O,PSA}}^{\text{mmW},t_{\text{row}}} (L) = \frac{\eta_{\text{CE,O,proposed}}^{\text{mmW},t_{\text{row}}} (L)}{\eta_{\text{CE,O,proposed}}^{\text{mmW}} (L)},
\]

\[
\eta_{\text{CE,O,proposed}}^{\text{mmW},t_{\text{row}}} (L) = \frac{\eta_{\text{CE,O,proposed}}^{\text{mmW},t_{\text{row}}} (L)}{\eta_{\text{CE,O,proposed}}^{\text{mmW}} (L)}.
\]

4.6. Implementation Outlook. The implementation of the proposed technique depends on how nodes in the system coordinate with each other. There are mainly two coordination techniques, namely, centralized and distributed [20]. In centralized coordination, nodes cannot communicate with each other directly. Rather, they communicate via a central entity also termed as spectrum controller (e.g., the NRA) that controls the allocation of spectrum to all nodes connected to it. Usually, centralized coordination is useful for static spectrum sharing where spectrum updates of nodes do not need to be addressed so frequently. Centralized allocation suffers from higher protocol/infrastructure complexity as well as long delay. Moreover, in centralized coordination, there is a possibility of single-node failure. In contrast, distributed coordination, nodes communicate with each other directly in a distributed manner. Distributed coordination is used to update the status of nodes locally and frequently. However, distributed spectrum sharing suffers from large control signaling overhead due to the exchange of information among nodes, which increases with an increase in the size of coordinated nodes.

For implementing the proposed technique, in the primary level, the countrywide spectrum $M_{C,\text{max}}$ is allocated to each MNO $M_{o,\text{licensed}}$ centrally by the NRA based on their respective user demand $N_{o,\text{MBS}}$ at each renewal term $t_{\text{row}}$, with a minimum time duration of 3 to 6 months. At the secondary level, the allocated spectrum to each MNO $M_{o,\text{licensed}}$ is then shared among each other in a distributive manner. Due to the infrequent change in the spectrum allocation to each MNO, the centralized spectrum allocation is preferable in level 1. On the other hand, the allocated spectrum per MNO in level 2 is shared further among all MNOs. Due to the fast change in the radio access networks, the status of spectrum sharing in level 2 for each MNO needs to be changed very frequently to receive the best quality signals. Because cellular standards transmit in milliseconds level, and the distributed coordination is delay-sensitive, distributed coordination is more appropriate for implementing on the radio access side for sharing spectrum. In this regard, small cells of each MNO keep sensing the presence of UEs of other MNOs within each apartment. If no UE of a small cell is detected within an apartment, the corresponding small cell can share its allocated spectrum with other active small cells serving their users within the same apartment. Figure 3 shows an illustrative implementation of the proposed two-level DSAS technique considering that UEs of small cells of
MNO 1 and MNO 3 are absent such that their licensed spectrum is shared with a small cell of MNO 2 within the same apartment.

5. Performance Evaluation

5.1. Simulation Parameters and Assumptions. Table 5 shows the simulation parameters and assumptions (consistent with the recommendations from the standardization bodies), which are considered for the performance evaluation of the proposed DSAS technique. More specifically, we consider the 28-GHz band because of the favorable signal propagation characteristics indoors and as a potential mmWave band for fifth generation (5G) and upcoming 6G [37]. Similarly, due to its large coverage and the smaller number of handoffs, 2 GHz is considered outdoors. Furthermore, because of the less multipath fading effect indoors, we consider the line-of-sight (LOS) large-scale path loss model for the 28-GHz signals within buildings. Furthermore, due to its small coverage area and less multipath fading effect, we assume that the 28-GHz mmWave signal propagation characteristic of each indoor small cell is similar within any building. Also, because of a high external wall penetration loss of a building and a low transmission power of any in-building small cell, the 28-GHz spectrum is considered being reused to small cells located in adjacent buildings.

We consider that four MNOs are operating in a country even though, in practice, the proposed technique applies to any number of MNOs in a country. In addition to licensing the 2-GHz spectrum, each MNO owns its license for the 28-GHz spectrum allocated according to its number of subscribers for a certain renewal term in level 1 or primary spectrum allocation. Furthermore, each MNO owns or controls elements of the wireless network infrastructure, backhaul infrastructure, billing, and customer care required to provide service to its subscribers over the allocated license spectrum. Furthermore, each MNO is responsible for the day-to-day network operations and maintenance to ensure the quality-of-experience of its users.

Moreover, the 28-GHz mmWave spectrum of 200 MHz is considered countrywide to evaluate performances of the proposed technique although, in practice, the amount of the 28-GHz spectrum countrywide can be huge, that is, in the GHz level [43]. Furthermore, for the simplicity in analysis and closed-form solution, each small cell of an MNO is assumed to serve the maximum of one UE at a time. Moreover, we consider that the existence of any combination of four UEs one from each MNO in an apartment of a building is equally likely.

![Figure 3: An illustration of the implementation of the proposed DSAS technique.](image-url)
Table 5: Default parameters and assumptions.

| Parameters and assumptions | Value |
|----------------------------|-------|
| **All MNOs countrywide** | 200 MHz and 10 MHz |
| Spectrum bandwidth in the 28 GHz (countrywide) & 2 GHz (per MNO) | NC, max and 4 |
| Total number of subscribers and MNOs in a country | 40% of NC, max for MNO 1, 30% of NC, max for MNO 2, 20% of NC, max for MNO 3, and 10% of NC, max for MNO 4 |
| Total subscribers of MNOs | 40% of NC, max for MNO 1, 30% of NC, max for MNO 2, 20% of NC, max for MNO 3, and 10% of NC, max for MNO 4 |
| **Per MNO countrywide** | 2 GHz (per MNO) 200MHz and 10MHz |
| E-UTRA simulation case | Third-generation partnership project (3GPP) case 3 |
| Cellular layout, intersite distance (ISD), transmit direction | Hexagonal grid, dense urban, 3 sectors per macrocell site, 1732 m, and downlink |
| Carrier frequency | Licensed 2-GHz non-line-of-sight (NLOS) microwave spectrum band for macrocells and picocells, licensed 28-GHz line-of-sight (LOS) mmWave spectrum band for small cells |
| Number of cells | 1 macrocell, 2 picocells, 48 small cells per building |
| Total BS transmit power | 46 for macrocell, 37 for picocells, 19 for 28 GHz for small cells |
| Cochannel small-scale fading model | Frequency selective Rayleigh for 2-GHz NLOS spectrum for macrocells and picocells, no small-scale fading for 28-GHz LOS spectrum for small cells |
| External wall penetration loss | 20 dB for 2-GHz spectrum |
| Path loss | Outdoor PL (dB) = 15.3 + 37.6log10R, R is in m |
| | Indoor macrocell PL (dB) = 15.3 + 37.6log10R + low, R is in m |
| | PBS and a UE PL (dB) = 140.7 + 36.7log10R, R is in km |
| | SBS and a UE PL (dB) = 61.38 + 17.97log10R, R is in m |
| Lognormal shadowing standard deviation (dB) | 8 for MBS2, 10 for PBS1, and 9.9 for 28-GHz LOS spectrum for SBS2–4,6 |
| Antenna configuration | Single-input single-output for all BSs and UEs |
| Antenna pattern (horizontal) | Directional (120°) for MBS1, omnidirectional for PBS1 and SBS1 |
| Antenna gain plus connector loss (dBi) | 14 for MBS2, 5 for PBS1, 5 for SBS1,3,5,6 |
| UE antenna gain | 0 dBi (for 2 GHz), 5 dBi (for 28 GHz, Biconical horn) |
| UE noise figure | 9 dB (for 2 GHz) and 10 dB (for 28 GHz), 3 km/hr |
| UE speed | 30 |
| Total number of macrocell UEs | 40 m (radius), 2/15 |
| Picocell coverage and macrocell UEs offloaded to all picocells | 35% |
| Indoor macrocell UEs | 6 |
| Number of buildings | 8 |
| Number of floors per building | 1 |
| Number of apartments per floor | 48 |
| Number of SBSs per apartment | 10 \( \sqrt{2} \) m (When located diagonally) and 10 m (when located on the same line) for the intrafloor level and 3 m for the interfloor level |
| Total number of SBSs per building | Static 48 per MNO |
| Area of an apartment | Proportional fair (PF) and full buffer |
| 3D multistory building and SBS models (for regular square-grid structure) | Closed subscriber group (CSG) femtocell BSs |
| ISD for small cells | Ideal 1 ms, 100 ms, 6 months |
| Small cell implementation | 8 ms |
| Number of small cell UEs per building | Taken from [38], 2 from [39], 3 from [40], from [41], from [42], from [11], from [29].

Notes:
- TTI: scheduler time constant, \( t_c \), \( t_{agg} \) and total simulation run time.
We consider the full buffer model such that resource schedulers can be assumed to have user traffic to serve at any time over the observation period. Also, due to ensuring balance performances between the throughput and the fairness in radio resource allocations, we consider the proportional fair (PF) resource scheduler. Finally, using Table 5, we generate the performance results by a simulator built by using the computational tool MATLAB R2012b version running on a personal computer.

Table 6: Total spectrum per MNO due to applying level 2 spectrum sharing.

| MNO index | Licensed spectrum (in the percentage of $M_{C_{\max}}$) (%) | Shared spectrum (in the percentage of $M_{C_{\max}}$) (%) | Total spectrum (in the percentage of $M_{C_{\max}}$) (%) |
|-----------|----------------------------------------------------------|-------------------------------------------------------|-----------------------------------------------------|
| MNO 1     | 40                                                       | 30                                                    | 70                                                  |
| MNO 2     | 30                                                       | 35                                                    | 65                                                  |
| MNO 3     | 20                                                       | 40                                                    | 60                                                  |
| MNO 4     | 10                                                       | 45                                                    | 55                                                  |
| All MNOs  | 100                                                      | 150                                                   | 250                                                 |

![Figure 4: Countrywide performance improvement factors, in terms of CP, SE, EE, and CE, for $L = 1$.](image)

![Figure 5: Countrywide average SE responses for $L > 1$.](image)

![Figure 6: Countrywide average EE responses for $L > 1$.](image)

5.2. Performance Results. The following scenarios are considered for the performance evaluation of DSAS:

(i) When considering only level 1 spectrum allocation (i.e., PSA)

(ii) When considering both levels (i.e., DSAS)

(iii) When considering only static licensed spectrum allocation (i.e., SLSA)

Figure 4 shows countrywide performance improvement factors in terms of the average capacity (CP), SE, EE, and CE.
due to applying the PSA, as well as the proposed DSAS, techniques in comparison with that of SLSA for \( L = 1 \) of 0 MNOs countrywide. Using (11) and (12), since SE is directly proportional to \( CP \), from Figure 4, PSA and DSAS improve both CP and SE performances by 22.79% and 204.78%, respectively. Likewise, using (13) and (17), since EE and CE are inversely proportional to CP, PSA and DSAS improve both EE and CE performances by 18.56% and 67.19%, respectively. These countrywide performance improvements of PSA and DSAS over SLSA can be clarified by the following.

For SLSA, each MNO is assigned with 25% of the total 28-GHz mmWave spectrum countrywide as a baseline. However (using Table 5), the number of subscribers of MNO 1, MNO 2, MNO 3, and MNO 4 are 40%, 30%, 20%, and 10%, respectively, of \( N_{\text{C}, \text{max}} \) at \( t_{\text{raw}} \). Now, using (2), for any MNO \( o \), \( M_{\text{raw}} \) depends on its \( N_{\text{raw}} \) at \( t_{\text{raw}} \) causing MNO 1 and MNO 2 to suffer from necessary spectra, while MNO 3 and MNO 4 to yield unnecessary spectra with respect to their corresponding actual demand. This results in underutilizing the licensed mmWave spectrum allocated applying the SLSA to MNOs 3 and 4 because of not using the allocated spectrum of 5% of \( M_{\text{C}, \text{max}} \) by MNO 3 and 15% of \( M_{\text{C}, \text{max}} \) by MNO 4. This, in turn, leads to a reduction in their CP and SE responses [5].

On the contrary, MNO 1 and MNO 2 operate on a shortage of spectrum of 15% and 5%, of \( M_{\text{C}, \text{max}} \), respectively, making them not being able to serve their respective actual user demand. Overall, when employing the traditional SLSA technique, the aggregate CP and SE of all MNOs \( O = 4 \) decrease because of the underutilization of a total of 20% of \( M_{\text{C}, \text{max}} \) by MNO 3 and MNO 4. Moreover, because EE and CE change inversely with a change in CP, both the energy required to transmit a bit and the cost imposed to achieve per bps capacity increase with a decrease in average CP of all MNOs countrywide when applying the SLSA.

On the contrary, when employing the proposed PSA, each of the four MNOs is assigned with the amount of licensed 28-GHz spectrum corresponding to its number of subscribers (i.e., 40%, 30%, 20%, and 10%) of the countrywide mmWave spectrum for MNO 1, MNO 2, MNO 3, and MNO 4, respectively, at \( t_{\text{raw}} \) allowing each of the MNOs to operate on its required licensed mmWave spectrum. Similarly, when employing the SSS (on top of the PSA) to in-building SBSs of four MNOs, using Table 3, the maximum amount of shared spectrum for MNO 1 that can be obtained is 30% of \( M_{\text{C}, \text{max}} \) for any observation time \( Q \). Following Table 3 for MNO 1, it can be found that the maximum amount of shared spectra that can be obtained for MNOs 2, 3, and 4 are 35%, 40%, and 45% of \( M_{\text{C}, \text{max}} \), respectively, for any observation time \( Q \). Hence, the sum of the total shared spectrum countrywide that can be obtained due to the SSS is 150% (i.e., 30% + 35% + 40% + 45%) of \( M_{\text{C}, \text{max}} \), resulting in a total of 250% of \( M_{\text{C}, \text{max}} \) (i.e., the total licensed spectrum of 100% and the shared spectrum of 150% of \( M_{\text{C}, \text{max}} \)) as shown in Table 6. From Table 6, even though the shared spectrum increases with a decrease in the allocated spectrum to an MNO in PSA, its overall total spectrum increases due to the SSS. Since the SSS increases the mmWave spectrum countrywide substantially by 150% and the proposed DSAS technique employs both PSA and SSS, DSAS improves all these performance metrics in Figure 4 significantly. This justifies the use of the two-level spectrum allocation and sharing technique (i.e., DSAS) to the 28-GHz mmWave spectrum countrywide.

Besides, SE and EE performances of the level 1 spectrum allocation, the proposed DSAS technique, and the traditional SLSA technique countrywide are shown in Figures 5 and 6, respectively, when reusing the same 28-GHz spectrum to SBSs in each building of each MNO for \( L = 1 \). It can be found that, for all approaches, as \( L \) increases, SE increases while EE improves noticeably for low values and becomes nearly steady for high values of \( L \). Like Figure 1 for \( L = 1 \), the proposed DSAS technique for \( L > 1 \) is influenced significantly by the SSS as compared to the PSA and outperforms all other techniques in terms of SE and EE metrics.

### 5.3. Performance Comparison

It is expected that the future 6G network would offer a tenfold average SE of 270–370 bps/Hz [28, 44], as well as a tenfold average EE of 0.3 \( \mu \text{J/b} \) [37], as compared to 5G [45, 46]. Assume that \( \sigma_{\text{SE}, \text{6G}} = 370 \text{ bps/Hz} \) denotes the required average SE and \( \sigma_{\text{EE}, \text{6G}} = 0.3 \mu \text{J/b} \) denotes the required average EE for 6G [11, 29]. Table 7 shows the required value of \( L \) for SLSA, PSA, and DSAS techniques to fulfill both the requirements of SE and EE for 6G using Figures 5 and 6. Let \( Q_{\text{SE}, o, \text{raw}} \) and \( Q_{\text{EE}, o, \text{raw}} \) denote the achievable SE and EE per MNO at time \( t_{\text{raw}} \), respectively. From Figures 5 and 6, since the responses of \( Q_{\text{SE}, o, \text{raw}} \) and \( Q_{\text{EE}, o, \text{raw}} \) are opposite to each other, the required value of \( L \) that can satisfy both SE and EE requirements for the 6G mobile networks is the maximum value of \( L \) that is, the value of \( L \) corresponding to satisfying max \( (\frac{Q_{\text{SE}, o, \text{raw}}}{Q_{\text{EE}, o, \text{raw}}}) \).

From Table 7, the required number of buildings of SBSs per MNO in a country of four MNOs, that is, max \( (Q_{\text{SE}, o, \text{raw}}/Q_{\text{EE}, o, \text{raw}}) \), is 37, 30, and 13 for SLSA, PSA, and DSAS techniques, respectively, to fulfill requirements for 6G mobile networks’ both SE and EE performance metrics. This implies that by applying the PSA and the proposed DSAS techniques and using

| Technique | \( \sigma_{\text{SE}, o, \text{raw}} \) \( \geq \sigma_{\text{SE}, 6G} \) | \( \sigma_{\text{EE}, o, \text{raw}} \) \( \leq \sigma_{\text{EE}, 6G} \) | \( L_{\text{max}}(\sigma_{\text{SE}, o, \text{raw}}, \sigma_{\text{EE}, o, \text{raw}}) \) | (1 – Technique/SLSA)% |
|-----------|----------------|----------------|----------------|----------------|
| SLSA      | 37             | 1              | 37             | 0.0            |
| PSA       | 30             | 1              | 30             | 18.92          |
| DSAS      | 13             | 1              | 13             | 64.86          |
(1 – Technique/SLSA)%, the prospective requirements of SE and EE for 6G can be fulfilled by reusing the 28-GHz spectrum to 18.92% and 64.86% less number of buildings of SBSs than that required by the SLSA.

6. Conclusion

In this article, we propose a two-level dynamic spectrum allocation and sharing (DSAS) technique to address spectrum liberalization in the primary spectrum allocation (PSA) (i.e., in level 1), whereas spectrum flexibility in the secondary (i.e., level 2) spectrum sharing (SSS) for more progressive spectrum management policies to improve the overall utilization of 28-GHz spectrum countrywide. In PSA, an MNO is allocated to the 28-GHz spectrum in accordance with its subscribers’ number at any renewal term, whereas, in SSS, any MNO’s allocated spectrum in the PSA can be allowed to share with SBSs in a building of another MNO subject to avoiding cochannel interference between their users.

The optimal value of the licensed 28-GHz spectrum for each MNO in the PSA is expressed, as well as the amount of shared spectrum for in-building UEs of each MNO in the SSS is estimated. Numerous system-level performance metrics for the proposed DSAS and the traditional SLSA techniques are derived along with discussing the implementation perspectives of DSAS. The overall countrywide average capacity, SE, EE, and CE performance improvements of DSAS over that of SLSA are then shown. More specifically, since SE is directly proportional to CP, PSA and DSAS improve both CP and SE performances by 22.79% and 204.78%, respectively. Likewise, since EE and CE are inversely proportional to CP, PSA and DSAS improve both EE and CE performances by 18.56% and 67.19%, respectively. Finally, we show that, by applying the proposed DSAS technique, the prospective requirements of SE and EE for 6G mobile networks can be achieved by reusing the 28-GHz spectrum to 64.86% less number of buildings of SBSs than that required by the SLSA.

Note that both the renewal term and the number of subscribers per MNO have a direct impact on the performance of the proposed technique. More specifically, due to being a competitor of one another, MNOs may not be willing to share information of their subscribers with each other. Moreover, MNOs may have different opinions on a common renewal term to update their allocated mmWave spectrum in level 1. Hence, defining an optimal renewal term, as well as the exact number of subscribers per MNO in any renewal term, is a major challenge of the proposed technique. In this regard, NRA may take the responsibility to resolve both issues by imposing a common renewal term on all MNOs and not disclosing the subscribers’ statistics of one MNO to another. Another major concern of the proposed technique is the coordination among small cells of all MNOs to update the presence of UEs in order to avoid cochannel interference in an apartment. In this regard, since nodes can communicate locally in the distributed coordination, this issue can be resolved by defining an optimal size of a group of small cells in a building for coordination locally. We will address the above issues by carrying out a Proof-of-Concept (POC) of the proposed implementation of the DSAS technique in our further study.

Appendix

A. Proof 1

Let $n$ denote a dummy variable representing the number of MNOs countrywide (to analyze Table 3 in SSS) such that $n = (O - 1)$. Then, Table 3 corresponding to $n$ follows a left-justified Pascal’s triangle [47] as shown in Table 4 for $O = 10$ if the same amount of spectrum $M$ is allocated to each MNO [31]. The entry in a row $n$ and column $k$ (where $k$ is an integer between 0 and $n$, i.e., $n \geq k \geq 0$) in Table 4 is defined by the binomial coefficient as given below:

$$C(n, k) = \binom{n}{k} = \frac{n!}{k!(n-k)!} \tag{A.1}$$

where each entry $\binom{n}{k}$ in a row $n$ of Table 4 denotes a multiplier corresponding to a component of the shared spectra given by $\{0, M, 2M, \ldots, (n-1)M, nM\}$ for a UE of an MNO $o$ in SSS for $n = (O - 1)$.

Note that by assuming a unique nonzero entry 1 in row 0 (i.e., the topmost row), we can easily develop Table 4 for any number of MNOs $O$ just by adding two adjacent numbers to the left above with each entry of each subsequent row, taking blank numbers as 0 [47]. Now, from (A.1), we can find the following:

$$\sum_{k=0}^{\frac{n}{2}} \binom{n}{k} = \left( \binom{n}{0} + \binom{n}{1} + \binom{n}{2} \right) + \cdots + \binom{n}{n} = 2^n. \tag{A.2}$$

Since the sum of the entries in a row $n$, that is, $\binom{n}{k}$, in Table 4 is $2^n$, it satisfies the total number of multipliers of all components of the shared spectra for a UE of an MNO $o$ for $O = n + 1$ MNOs in a country. Moreover, it also fulfills the condition of Pascal’s triangle for the summation of the entries in the nth row of the triangle [47].

Hence, for an arbitrary value of $O$, using Pascal’s triangle, we can find the set of multiplication entries $\left\{ \binom{n}{0}, \binom{n}{1}, \binom{n}{2}, \ldots, \binom{n}{n} \right\}$ for any row $n = (O - 1)$ in Pascal’s triangle to multiply it with the set of the corresponding components of the shared spectra given by $\{0,$
M, 2M, …, (n − 1) M, nM] for a small cell UE of an MNO o as shown in Table 4. In other words, the complete set of the components of the shared spectra for a small cell UE of an MNO o in an apartment of a building coexisting with UEs of MNOs O \{o can be expressed as [31]

\[
\left\{ \binom{n}{0} \times 0 \right\}, \binom{n}{1} \times (M), \binom{n}{2} \times (2M) \ldots, \binom{n}{n} \times (nM) \right\}.
\]

(A.3)

Note that we define a set of components of the shared spectra complete when the set includes all the possible number of times each of the components of the shared spectrum can occur for any n, that is, when each component is multiplied by its corresponding binomial coefficient in Pascal’s triangle as shown in Table 4. For example, for O = |O| = 4, n = 3 such that the set of multipliers in Pascal’s triangle is given by \{3, 3, 3, 1\}, which corresponds to the set of the components of the shared spectra \{0, M, 2M, 3M\}. Hence, as shown in Table 4, the complete set of the components of the shared spectra for a small UE of an MNO o is given by \{3, 3, 3, 1\} \times (M) \times \binom{3}{2} \times (2M) \times \binom{3}{3} \times (3M)\}

(i.e., \{1(0), 3(1), 3(2), 1(3)\}). Now, in Table 3, if each MNO is considered allocating to the same amount of spectrum such that \(M_{t_{\text{raw}}} = 2M_{s_{\text{raw}}} = M_{b_{\text{raw}}} = M_{u_{\text{raw}}} = 0.4\)M_{C_{\text{max}}}, it can be found that the set of the components of the shared spectra for a small cell UE of an MNO o at \(t_{\text{raw}}\) is given by \{1(0), 3(1), 3(2), 1(3)\}, which is the same as that found from Table 4. Hence, Table 3 can be formed using Pascal’s triangle if each MNO is considered allocating to an equal amount of spectrum.

**B. Proof 2**

Assume that the spectra allocated to MNO 1, MNO 2, MNO 3, and MNO 4 in PSA are, 40% of \(M_{C_{\text{max}}} \), 30% of \(M_{C_{\text{max}}} \), 20% of \(M_{C_{\text{max}}} \), and 10% of \(M_{C_{\text{max}}} \), respectively, at any \(t_{\text{raw}}\). Hence, \(M_{t_{\text{raw}}} = 0.4M_{C_{\text{max}}}, M_{s_{\text{raw}}} = 0.3M_{C_{\text{max}},}

\(M_{b_{\text{raw}}} = 0.2M_{C_{\text{max}}}, \) and \(M_{u_{\text{raw}}} = 0.1M_{C_{\text{max}}}\). Using Table 3 for \(\bar{O} = 4\), we can now estimate the total spectrum of all MNOs in a country due to applying SSS during the observation time \(Q\) at any \(t_{\text{raw}}\) as shown in Table 8. From Table 8, for \(u_1\) of MNO 1, the licensed spectrum, the shared spectrum, and the total spectrum are given by \(3.2M_{C_{\text{max}}}, \)

\(2.4M_{C_{\text{max}}}, \) and \(5.6M_{C_{\text{max}}}\) respectively.

Likewise, following Table 8, the licensed spectrum, the shared spectrum, and the total spectrum are given by \(2.4M_{C_{\text{max}}}, \) \(2.8M_{C_{\text{max}}}, \) and \(5.2M_{C_{\text{max}}}\) for \(u_2\) of MNO 2; \(1.6M_{C_{\text{max}}}, \) \(3.2M_{C_{\text{max}}}, \) and \(4.8M_{C_{\text{max}}}\) for \(u_3\) of MNO 3; and \(0.8M_{C_{\text{max}}}, \) \(3.6M_{C_{\text{max}}}, \) and \(4.4M_{C_{\text{max}}}\) for \(u_4\) of MNO 4, respectively. Hence, due to applying SSS, the total spectrum of all MNOs 1, 2, 3, and 4, each assigned with an amount of spectrum different from that of the other, is given by

\[
M_{O_{\text{raw}}} = \sum_{o=1}^{4} M_{o_{\text{raw}}} = (5.6 + 5.2 + 4.8 + 4.4)M_{C_{\text{max}}} = 20M_{C_{\text{max}}}.
\]

Similarly, from Table 8, the total spectrum of all MNOs, 1, 2, 3, and 4, due to applying SSS when each MNO is assigned with the same amount of spectrum is given by

\[
M_{O_{\text{raw}}} = \sum_{o=1}^{4} M_{o_{\text{raw}}} = (4 \times 5.0)M_{C_{\text{max}}} = 20M_{C_{\text{max}}}.
\]

(B.2)

**Data Availability**

Data, primarily, in the form of numerous simulation assumptions and parameters reported previously by the standardization bodies, including third-generation
partnership project (3GPP) [38, 39] and International Telecommunication Union–Radio communication sector (ITU–R) [42], included and detailed within the article in Table 5, were used to carry out the performance evaluation of this study. Other prior studies than these above [38, 39] were cited at relevant places within the text as references [11, 28, 29, 40–42, 44–46]. No data other than these were used to evaluate the performance studies. Taking into account all these parameters and assumptions, the performance results were generated by a simulator running on a personal computer, which was built by the author using the standard computational tool MATLAB R2012b. MATLAB codes are not publicly available. However, supports for writing MATLAB instruction codes can be provided over the emails querying directly to the author at rony107976@gmail.com.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this article.

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