

Research Article

Independence and Fairness Analysis of 5G mmWave Operators Utilizing Spectrum Sharing Approach

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The spectrum sharing approach (SSA) has emerged as a cost-efficient solution for the enhancement of spectrum utilization to meet the stringent requirements of 5G systems. However, the realization of SSA in 5G mmWave cellular networks from technical and regulatory perspectives could be challenging. Therefore, in this paper, an analytical framework involving a flexible hybrid mmWave SSA is presented to assess the effectiveness of SSA and investigate its influence on network functionality in terms of independence and fairness among operators. Two mmWave frequencies (28 GHz and 73 GHz) are used with different spectrum bandwidths. Various access models have been presented for adoption by four independent mobile network operators that incorporate three types of spectrum allocation (exclusive, semipooled, and fully pooled access). Furthermore, an adaptive multi-state mmWave cell selection scheme is proposed to associate typical users with the tagged mmWave base stations that provide a great signal-to-interference plus noise ratio, thereby maintaining reliable connections and enriching user experience. Numerical results show that the proposed strategy achieves considerable improvement in terms of fairness and independence among operators, which paves the way for further research activities that would provide better insight and encourage mobile network operators to rely on SSA.

1. Introduction

Future mobile data usage and traffic growth are driven by diverse and innovative technologies and services, such as smart cities, health care, autonomous driving, augmented reality, virtual reality, and Internet of things [1]. However, today's extremely limited spectrum bandwidth at low frequencies (<6 GHz) can no longer accommodate novel and rapidly evolving applications [2]. This challenge underlines the need for freeing up additional spectrum to cope with the stringent requirements of bandwidth-hungry applications. In response to the bounded amount of spectrum, mmWave frequency bands have been recently introduced as an attractive enabling technology to address the spectrum shortage [3] because it has

an ample amount of available spectrum with a multigigahertz range [4, 5]. Despite such wide spectrum range, it is still not unlimited if other services that utilize the same bands are considered [6]. In addition, the inefficiency of spectrum utilization is expected to occur remarkably in mmWave bands if a large chunk of spectrum is exclusively granted to a single independent mobile network operator (IMNO) [7]. Accordingly, spectrum sharing approach (SSA) is an option that can overcome such issue in a cost-effective manner [8]. However, pursuing such approach in 5G mmWave cellular networks is a major decision that requires extensive research to study its effectiveness and implications from technical, regulatory, and economic perspectives. Achieving considerable improvement in spectrum utilization via SSA without sacrificing the merits

associated with traditional spectrum allocation (e.g., exclusive access) remains a major challenge that should be solved in a joint manner [9].

Several studies on the assessment of SSA implementation in mmWave communications have recently been conducted. In [10], a realistic indoor propagation channel and antenna models for mmWave networks were adopted along with link-specific context coordination to simulate an internetwork spectrum sharing strategy. Preliminary results demonstrated the viability of the proposed strategy in maximizing the throughput and eliminating the interference among operators.

Similarly in [6], many aspects regarding the technical enablers of SSA were addressed (e.g., beam directionality, base station (BS) density, and coordination) to study their influence on a set of network functionalities. Results proved the possibility of this approach in improving spectrum usage compared with the exclusive access spectrum allocation. In addition, the importance of interoperator coordination, especially for cell edge users, was indicated. Different from the above studies, the potential success of uncoordinated SSA was investigated in [5, 6, 11–13]. These studies showed the effectiveness of mmWave characteristics along with the directional beamforming technique in reducing cross-operator interference among multi-IMNOs, thereby eliminating the need for coordination among operators.

On the contrary, the authors in [14] confirmed that without coordination, sharing the spectrum among multi-IMNOs with different mmWave BS (mBS) deployment densities remains a great challenge, particularly when the mBS density of the interfering operator is higher than the operator with low mBS density. This observation may discourage the low-density operator to share their spectrum unless a low interference level is maintained among the multi-IMNOs. Moreover, in [15], two different network densities (i.e., fixed individual and fixed combined) with two mmWave cellular operators were suggested to model multi-IMNOs with colocated BSs; these multi-IMNOs can be reproduced and extended to any set of operators that allow straightforward analysis of key performance metrics (e.g., SINR). The analysis showed that infrastructure and spectrum sharing is more convenient for high-rate applications rather than low-rate ones.

In the present work, we extend the prior studies detailed above and our work in [8]. New assumptions are considered regarding the utilization of the hybrid mmWave spectrum sharing access (HMSSA) strategy, different path-loss models (commonly used in the literature), network planning, and agility improvements of operators with an acceptable level of mBS density. We also propose two access models for adoption by multi-IMNOs. To the best of the authors' knowledge, this study is the first to provide an analysis and deep discussion of two major challenges that face the successful realization of spectrum sharing among multiple mmWave entities. These two challenges are independent and fair, which may discourage operators to share their spectrum unless an acceptable trade-off is attained.

2. System Models

In this section, the proposed analytical framework is divided into four parts to simulate and apply the proposed HMSSA strategy accurately. Details are as follows.

2.1. Network Model. To serve a recognizable area, we consider two tiers of multi-IMNOs given by M , and each operator's network m^{th} has two spectrum bandwidths based on two carrier frequencies (28 and 73 GHz) given by c . Without loss of generality, let $W^{\text{m},c}$ denote the total spectrum that is allocated to each operator m^{th} .

Let S_m be a set of mBSs of operator m^{th} and $S = \{S_1 \cup S_1 \dots \cup S_m\}$ be a set of all mBSs in the network. However, all operators have their own mBSs S_m that can operate optionally at the two aforementioned mmWave carrier frequencies (28 GHz and 73 GHz). Notably, all mBSs are densely deployed and distributed as grid-based in an overlapping area that provides high coverage and QoS to a large number of user equipments (UEs), such that the simulation area is $1.2 \text{ km} \times 1.2 \text{ km}$. Additionally, all mBSs and UEs are assumed to be powered by multiple antenna (8×8). Each mBS has the right to grant a part of its allocated spectrum $W^{\text{m},l}$ exclusively for users that belong to its operator in the lower mmWave band (28 GHz) and share a part of its allocated spectrum $W^{\text{m},h}$ semiorthogonally or fully orthogonally to the users that belong to that operator or to other operators in the higher mmWave band (73 GHz). Let u denote a set of outdoor UEs and $u = \{u_1 \cup u_1 \dots \cup u_m\}$, where u_m is a set of users of all operators. Each $u^{\text{th},m}$ is served by a set of mBSs S_m , which either belong to the same or to different network operators based on spectrum regulation and link quality.

2.2. Mathematical Model. In this study, two types of mathematical expressions have been considered. The first is related to basic mobile communications, and the second is related to the mmWave communication system. They are derived and rewritten to model the proposed strategy and the baseline environments optimally. In the context of determining the special behavior of the overall hybrid mmWave spectrum sharing system, capturing one or more snapshots helps in gaining more insight on such approach and its implications on user experience and operator's revenue. We consider the commonly used close-in reference distance path-loss model [16–18] to calculate the received signal power at the receiving antenna:

$$PL(d_{\text{us}})^{\text{m},c} = PL_{\text{fs}}(d_o) + 10 \times \gamma \times \log_{10}\left(\frac{d_{\text{us}}}{d_o}\right) + x_{\sigma}, \quad (1)$$

where $PL(d_{\text{us}})^{\text{m},c}$ denotes the radio propagation path loss in dB; d_{us} denotes the separation distance in meters; d_o denotes the close-in free space reference distance (1 m); $PL_{\text{fs}}(d_o)$ denotes the initial path loss in dB, which can be calculated using equation (2); γ denotes the radio propagation path-loss exponent; and x_{σ} denotes the zero mean Gaussian random variable with standard deviation in dB represented

by (σ) , given that a 10 dB shadowing margin is used in this work.

$$PL_{fs}(d_o) = 20 \times \log_{10}\left(\frac{4 \times \pi \times d_o}{\lambda}\right), \quad (2)$$

where λ denotes the wavelength of the carrier wave. The radio propagation path-loss exponent and wavelength of both mmWave frequencies (28 GHz and 73 GHz) are listed in Table 1.

After applying equation (1), the average received signal power at the receiver can be calculated as follows [19]:

$$Pr = P_t + G_t + G_r - PL. \quad (3)$$

However, equation (3) is rewritten to handle the hybrid configuration brought about by the utilization of hybrid mBS deployment as follows:

$$Pr_{us}^{m,c} = P_t^{m,c} + G_t^{m,c} + G_r^{m,c} - PL_{us}^{m,c}, \quad (4)$$

where $Pr_{us}^{m,c}$ and $P_t^{m,c}$ are the received and transmitted power of mBS $S^{th,m}$, respectively, that is, the mBS owned by operator m^{th} and operated at mmWave carrier frequency c and $G_t^{m,c}$ and $G_r^{m,c}$ are the linear gains of the transmitter and the receiver antennas in dBi, respectively.

To assess the feasibility of the proposed HMSSA strategy and characterize the performance of each operator of the multi-IMNOs, we consider the coverage probability as an indicator when $SINR >$ threshold. For example, user $u^{th,m}$, who associates with mBS $S^{th,m}$ that is owned by the same or different operator m^{th} and shares or exclusively grants a particular portion of their spectrum available in either 28 GHz or 73 GHz carrier frequencies (c), is in outage if the SINR of that user is below than zero. The SINR of user $u^{th,m}$ can be calculated as follows [20]:

$$\mathfrak{X}_{us}^{m,c} = \frac{Pr_{us}^{m,c}}{\sum_{n=1}^N I_{us}^{m,c} + \eta^{m,c}}, \quad (5)$$

where $\mathfrak{X}_{us}^{m,c}$ denotes the SINR and $\sum_{n=1}^N I_{us}^{m,c}$ denotes the aggregated interference received by receiver $u^{th,m}$ from all neighboring mBSs that operate at the same frequency band except for the serving mBS $S^{th,m}$, regardless if they belong to the same IMNO. Specifically, we assume that only a single beam comes from each mBS $S^{th,m}$ that interferes receiver $u^{th,m}$. $\eta^{m,c}$ denotes the additive white noise power of operator m^{th} for a carrier frequency c and is obtained as follows [19]:

$$\eta^{m,c} = 10 \times \log_{10}(KT_{sys}) + 10 \times \log_{10} W_{m,c} + NF^{m,c}, \quad (6)$$

where $10 \times \log_{10}(KT_{sys})$ for a given system temperature (17°C) equal to -174 dBm/Hz and NF_u denotes the noise figure of the $u^{th,m}$ with a value of 6 dB. The calculated values of the SINR $\mathfrak{X}_{us}^{m,c}$ provide further user channel capacity calculation; thus, the average rate of user $u^{th,m}$ can be calculated using the Shannon capacity theory as follows:

$$R_{us}^{m,c} = \Phi_s^{m,c} \times \left(\frac{W^{m,c}}{u_s^{th}}\right) \times \log_2(1 + X_{us}^{m,c}), \quad (7)$$

where $\Phi_s^{m,c}$ denotes the number of antenna elements in the connected mBS $S^{th,m}$; $W^{m,c}$ is the total amount of spectrum

TABLE 1: Path-loss exponent and wavelength parameters.

Frequency bands (GHz)	γ (dB)	λ (mm)
28	3.4	10.71
73	3.3	4.106

bandwidth of the specified m^{th} ; $R_{us}^{m,c}$ denotes the channel capacity of the $u^{th,m}$ channel; and u_s^{th} denotes the number of users connected to the tagged $S^{th,m}$.

2.3. HMSSA Strategy Configurations. In this section, we present the most important configurations of the proposed HMSSA strategy and its models in detail. Four multi-IMNOs are considered and distributed throughout the simulation area of 1.2 km \times 1.2 km. A square grid-based cell deployment topology is used to ensure high-quality network coverage and mimic the quickest possible cell deployment, such as installing cells on street lamp posts. Two access models are suggested for utilization by the four operators. Each operator shares a part of its own allocated spectrum $W^{m,c}$ with other operators and exclusively grants the remaining part to its own subscribers $u^{th,m}$, as detailed as follows:

- (i) *Model 1.* In this model, we assume that the same spectrum bandwidth (1 GHz) allocated to the four operators at the low frequency 28 GHz ($W^{m,\lambda}$) and at the high frequency 73 GHz ($W^{m,h}$). However, the spectrum at the low-frequency band of 28 GHz ($W^{m,\lambda}$) is divided evenly into four parts, each with 250 MHz to be granted exclusively to one of the four multi-IMNOs to avoid cochannel interference phenomenon with other adjacent IMNOs. Meanwhile, the spectrum at the high-frequency band of 73 GHz ($W^{m,h}$) is divided into two portions, each with 500 MHz. The first part is open (pooled/shared) for all multi-IMNOs, whereas the second part is divided into two portions, each portion is assigned as semipooled/shared by two multi-IMNOs. For example, the first part (250 GHz) is granted to OP1 and OP4, and the second part (250 GHz) is granted to OP2 and OP3 as shown in Figure 1.
- (ii) *Model 2.* In this model, we assume two different sets of spectrum, that is, $W^{m,\lambda} = 1$ GHz at the low-frequency band of 28 GHz, and $W^{m,h} = 1.5$ GHz at the high-frequency band of 73 GHz. The spectrum assignment is similar to that in Model 1 for the low-frequency band of 28 GHz. However, at the high-frequency band of 73 GHz, the spectrum is divided into two parts; one with 1 GHz and the second with 500 MHz. The first part is evenly divided into four parts, and each is granted to IMNOs with exclusive access only to its subscribers $u^{th,m}$. In this assignment, the cochannel interference is nonexistent. The remaining amount (500 MHz) of the spectrum at 73 GHz is shared/pooled among the four multi-IMNOs. However, in the case of open-access mode, cochannel interference will exist among all adjacent operators, as shown in Figure 2.

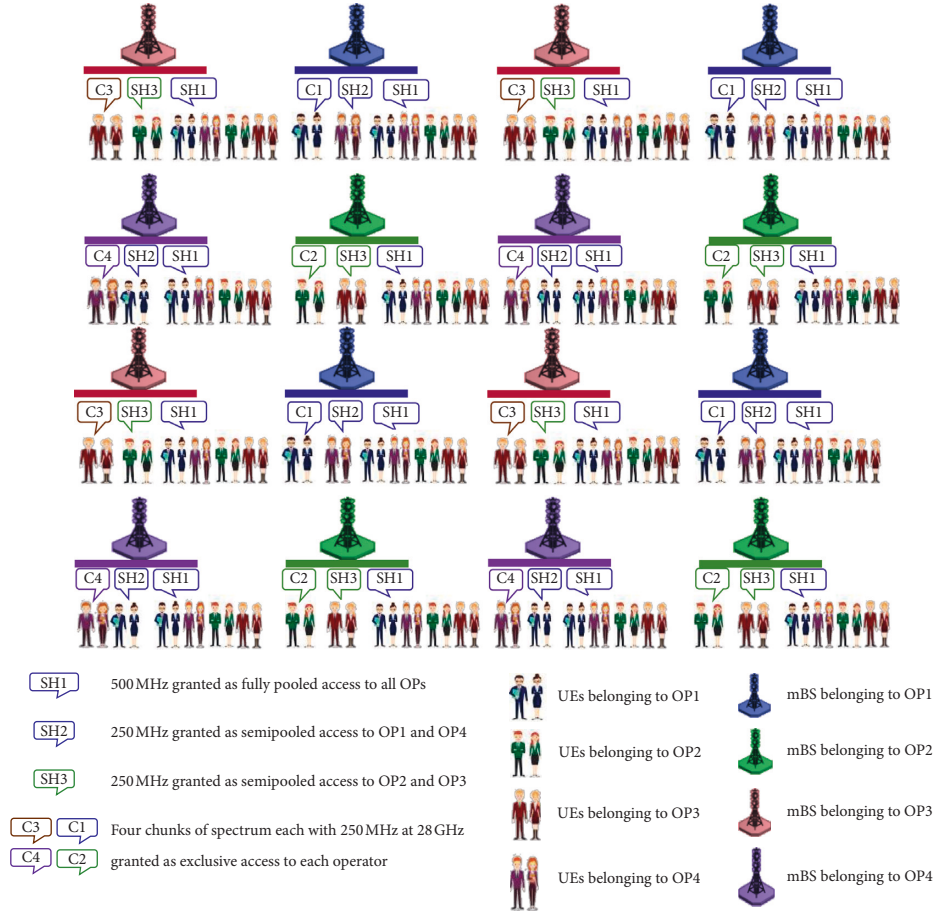


FIGURE 1: HMSSA Model 1.

2.4. UE-mmWave BS Association Scheme. In the proposed network configurations, rental or colocated-based mBS mode is suitable for adoption in of HMSSA strategy. In the first mode, each operator allows the rental of a part of its resources and infrastructures that are necessary for enabling efficient spectrum sharing among the multi-IMNOs. In the second mode, each operator has its own mBSs, which are hosted by other operators, provided that it is supplied with a part of the host's resources, location, cooling, and power supply.

In case of user and mBS association, the UEs that are subscribed to operator m^{th} have the right to associate with the mBS $S^{\text{th},m}$ that belongs to that operator or to other operators who share their resources based on the aforementioned modes (i.e., rent or colocated mode). In view of the proposed access strategy under Model 1, without loss of generality, three options are available for the users to associate with an mBS, which are described as follows:

- (i) UEs can associate with an mBS that offers an exclusive access to 250 MHz at 28 GHz that belongs to the same operator.
- (ii) UEs that are owned by one of a particular pair (OP1 and OP4 or OP2 and OP3, as assumed in this work)

can associate with an mBS that belongs to the same or to the second operator of the same pair, which offers a semipooled access of 250 MHz at 73 GHz and vice versa.

- (iii) UEs can associate with an mBS that belongs to OP1, OP2, OP3, or OP4, which offers a fully shared/pooled access of 500 MHz of the spectrum.

In Model 2, the UEs that are subscribed to the operator m^{th} have the right to associate with mBS $S^{\text{th},m}$ that belongs to that operator or to a different operator sharing the same frequency band based on the same constraints and options in Model 1; otherwise, the UEs that are owned by one of a particular pair can only associate with an mBS that belongs to the second operator of the same pair that offers an exclusive access of 250 MHz at 73 GHz and vice versa. In this case, the interference will be lower than that in Model 1, which utilizes semipooled spectrum access.

The user and cell association decisions are performed by using our proposed scheme, namely, AMMC-S, which relies on providing an optimal cell selection based on the offered signal quality as a function of SINR. For example, $u^{\text{th},1}$ is located closer to the four mBSs (i.e. $S^{\text{th},1}$, $S^{\text{th},2}$, $S^{\text{th},3}$, and $S^{\text{th},4}$) that belong to the four operators, as shown in Figures 3(a)–3(b). The $u^{\text{th},1}$ associates adaptively to $S^{\text{th},1}$ based on an exclusive



FIGURE 2: HMSSA Model 2.

access of 250 MHz at a 28 GHz carrier frequency that provides the highest SINR value to user $u^{th,1}$ as illustrated in Algorithm 1.

3. Results and Discussion

In this section, the performance of the proposed HMSSA strategy is assessed numerically in a typical mmWave scenario that supports two hybrid access models based on mBS distribution and spectrum allocation. Two key performance metrics (i.e., outage probability and average rate distributions) are considered in the evaluation and assessment process. These performance metrics are tailored for the assessment of operator’s independence and fairness, which is the main goal of this study. The related assumptions and simulation parameters are set, as shown in Table 2.

3.1. SINR Distributions. SINR represents a key system interference indicator to account for system interference and analyze its effect on network functionality. Typically, this is obtained by dividing the average received signal power by the sum between the noise power and the interfering power at the UE location as illustrated in equation (5). The lower SINR value the higher level of interference experienced by the UE from the adjacent mBSs. On the other hand, the SINR level is a measure to determine system coverage of the

wireless network which represents one of the most distinct parameters in the future 5G use cases; thus, studying its influence on 5G systems is required to assess system performance. In this context, the SINR distributions of the proposed strategy with respect to the two models have been studied, as detailed in the following subsections.

3.1.1. HMSSA Model 1. Figure 4 shows the outage probability of the four operators (i.e., OP1, OP2, OP3, and OP4) based on different allocated bandwidth percentiles (5%, 50%, and 95%) utilizing HMSSA under Model 1. The SINR distributions are averaged over a sufficient number of iterations to achieve the desired accuracy. Notably, the outage probability of the users that have exclusive access to the spectrum (250 MHz) at 28 GHz carrier frequency is lower than that of the semipooled and fully pooled spectrum access at a 73 GHz carrier frequency. This phenomenon is caused by the fact that semipooled access and fully pooled spectrum access are semiopen or fully open; hence, the amount of interference is larger than that in the exclusive spectrum access. The semipooled access strategy operates seven adjacent mBSs, whereas the fully pooled strategy operates fifteen. By contrast, only three mBSs operate in the exclusive access, except the serving mBS (see Figure 1). However, the location of user $u^{th,m}$ in terms of mBS $S^{th,m}$ generally plays a dominant role in minimizing outage probability. The fully

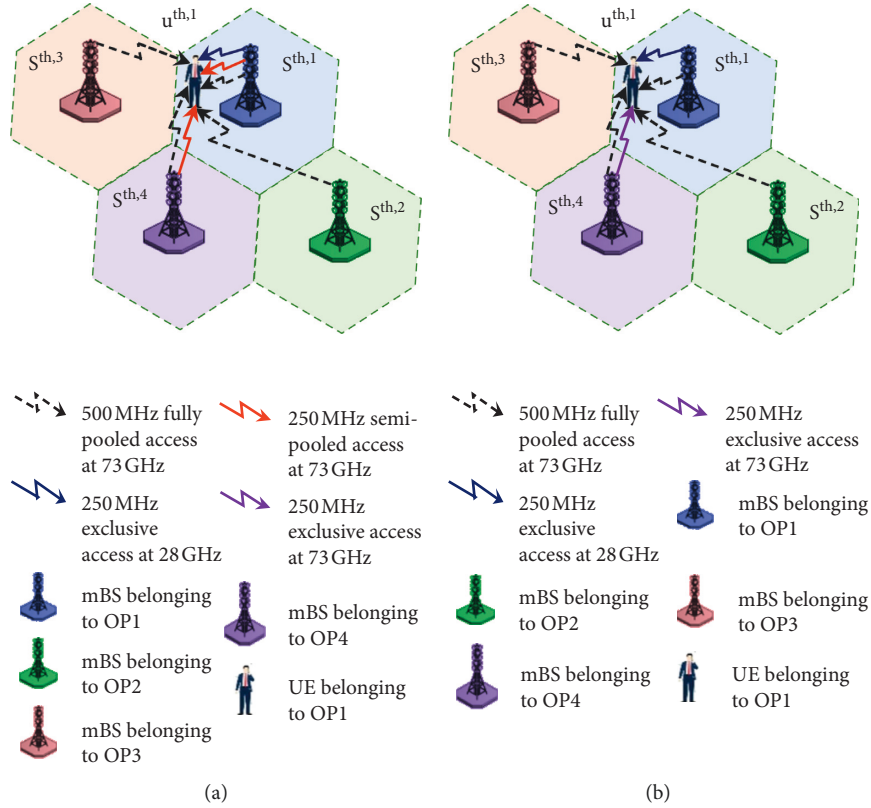


FIGURE 3: User-association options (a) HMSSA Model 1 (b) HMSSA Model 2.

Input: Set the initial parameters of $\forall m^{\text{th}} \in M$, $\forall S^{\text{th},m} \in S$, $\forall u^{\text{th},m} \in u$, $\forall W^{m,\lambda}$ and $W^{m,h} \in W^{m,c}$, $P_t^{m,c}$, NF_u

- (1) Deploy S , u of all operators throughout the simulation area ($1.2 \text{ km} \times 1.2 \text{ km}$);
- (2) **for** $\forall m^{\text{th}} \in M$ and $\forall u^{\text{th},m} \in u$ **do**
- (3) Compute the distance $\forall u^{\text{th},m}$ in terms of $\forall S^{\text{th},m}$ that belong to the same or different mobile network operator (MNO);
- (4) Compute $PL_{fs}(d_o)$, $PL(d_{us})^{m,c}$, and $Pr_{us}^{m,c}$ of $\forall u^{\text{th},m}$ according to equations (1), (2), and (4);
- (5) Compute $\mathfrak{X}_{us}^{m,c}$ of $\forall u^{\text{th},m}$ in terms of $\forall S^{\text{th},m}$ that belong to the same or different MNO using equation (5);
- (6) Associates $\forall u^{\text{th},m}$ to the tagged $S^{\text{th},m}$ that offers maximum $\mathfrak{X}_{us}^{m,c}$;
- (7) Compute $R_{us}^{m,c}$ of $\forall u^{\text{th},m}$ considering the spectrum amount weather $W^{m,\lambda}$ or $W^{m,h}$ and the spectrum access strategy (i.e., exclusive, semipooled, and fully pooled access) according to equation (7);
- (8) **end for**
- (9) Compute the outage probability of each operator as a function of SINR;
- (10) Compute the average rate distributions of each operator $\text{Avg}R^m$, where $m = \{1, 2, 3, \dots, M\}$;
- (11) Apply standard deviation formula using equation (10) for fairness assessment;
- (12) **Output:** Outage probability, Average rate distributions

ALGORITHM 1: Pseudocode of the HMSSA strategy and AMMC-S scheme implementation.

pooled spectrum access outperforms the semipooled spectrum access in some iterations, which occurs when the users are closer to an mBS $S^{\text{th},m}$ that belongs to different operator and only offers fully pooled access. For example, user $u^{\text{th},1}$ that subscribes to OP1, which is located extremely close to mBSs $S^{\text{th},2}$ and $S^{\text{th},3}$ owned by OP2 and OP3, will have a choice to associate with either $S^{\text{th},2}$ and $S^{\text{th},3}$, which have fully pooled spectrum access. Accordingly, the outage probability of the fully pooled spectrum access becomes lower than of the semipooled spectrum access.

In the proposed HMSSA strategy under Model 1, an additional flexible degree of freedom is utilized to bring advantages from all the available mBSs that operate at different carrier frequencies and spectrum assignments. Therefore, the outage probability is reduced considerably with SINR more than 3 dB of the cell edge user, which outperforms the most related works in [7, 11, 12, 15]. This result can be translated to an enhancement in the performance of the cell edge users. Hence, the coverage and data rate can be improved. Furthermore, the number of mBSs is also decreased, where only 16 mBSs are needed to cover a

TABLE 2: HMSSA and AMMC-S simulation parameters.

Parameters	Settings
mmWave BSs layout	Grid-based cell deployment
mmWave BSs density	16
# of operator	4
UE layout	Uniform random distribution
UE density	160 users
Simulation area	1.2 km × 1.2 km
Intersite distance (ISD)	300 m
mBS carrier frequency	28 GHz and 73 GHz
mBS transmit power	30 dB
Variant of white Gaussian noise	-174 dBm/Hz
mBS bandwidth	Model 1: 1 GHz for 28 GHz and 73 GHz Model 2: 1 GHz for 28 GHz and 1.5 GHz for 73 GHz

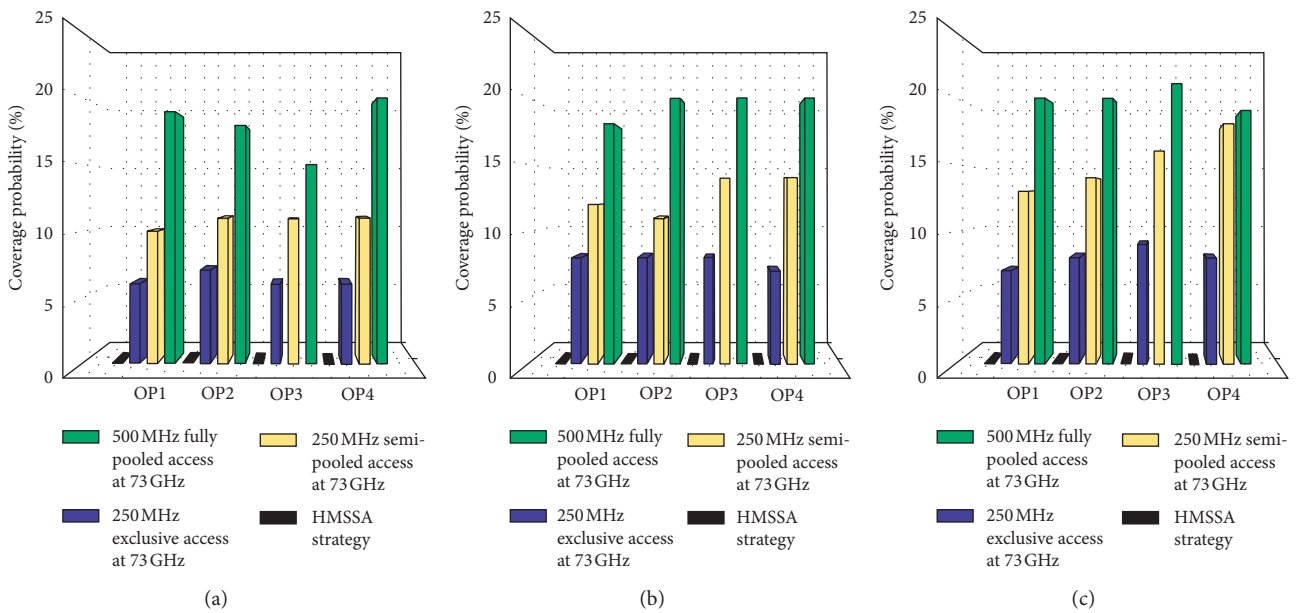


FIGURE 4: Outage probability percentage for all operators with different percentiles. (a) 5%, (b) 50%, and (c) 95% (Model 1).

1.2 km × 1.2 km area with good coverage which account less than the state of the arts [7, 11, 12, 15]. The outage probability percentages of OP1, OP2, OP3, and OP4 are zero (0%), as shown in Figures 4(a)–4(c). This significant maximization in the (SINR) performance is due to the hybrid spectrum portioning way that enables a flexible hybrid spectrum access strategies and allows for the availability of multiple links with different signal quality within a given transmission range. By adopting the proposed AMMC-S scheme, the UE association with a link that carries the highest SINR can be guaranteed and hence maintain ultrareliable level of connectivity which accounts as one of the most stringent future 5G constraints.

3.1.2. *HMSSA Model 2.* Model 2 is similar to Model 1. Except for the allocated spectrum amount. Moreover, in Model 2, each user can be associated with any mBS belongs to the same operator or to different operators based on one

of the two choices, that is, exclusive access to 250 MHz at 28 GHz and fully shared/pooled access to 500 MHz of the spectrum at 73 GHz carrier frequency or exclusive access to 250 MHz at 73 GHz and fully pooled access to 500 MHz of the spectrum at 73 GHz carrier frequency. Such restrictions in Model 2 help to improve the outage probability of the semipooled spectrum access. The outage probability of all operators that utilize the proposed strategy are kept zero (0%), as shown in Figures 5(a)–5(c), with some improvement in the SINR distributions (>6 dB). The obtained improvement in this model widens the gap with other spectrum access strategies (i.e., exclusive, fully pooled), thereby adding 3 dB to the cell edge users (compared with Model 1). This phenomenon is caused by the fact that the additional amount of spectrum at 73 GHz reduces the interference between the mBSs that operate at such frequency as the number of adjacent mBSs that operate in the same bands is reduced. Fifteen adjacent mBSs are operated by the fully pooled access strategy, whereas only three adjacent mBSs are

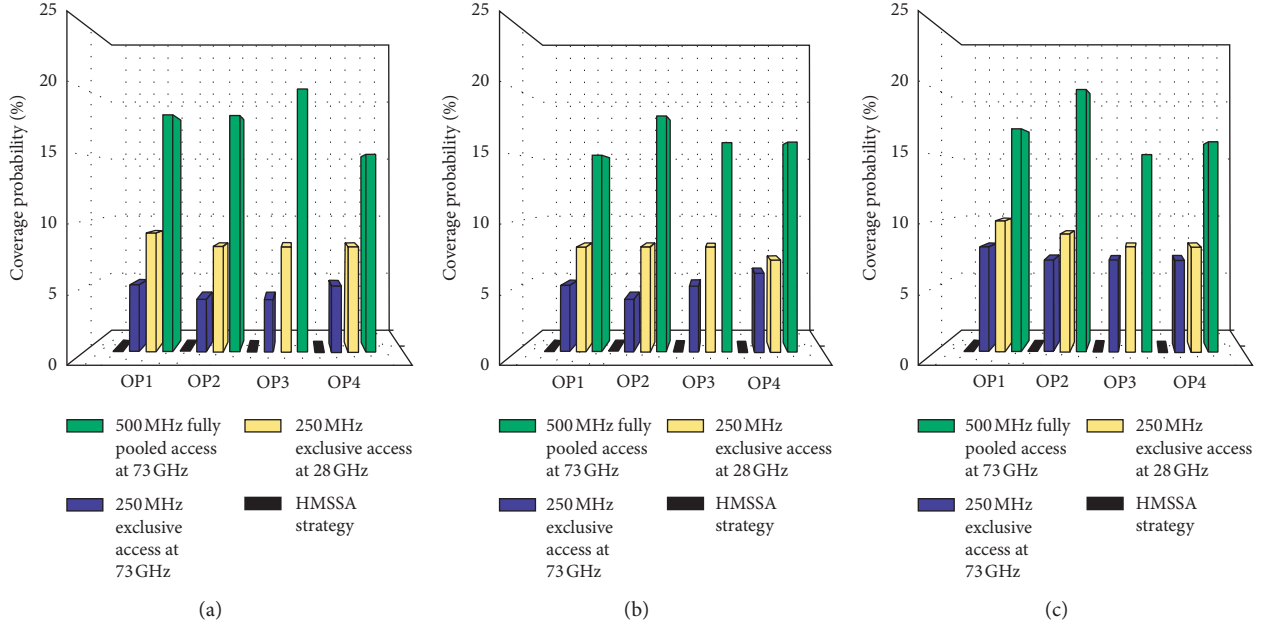


FIGURE 5: Outage probability percentage for all operators with different percentiles. (a) 5%, (b) 50%, and (c) 95% (Model 2).

operated by exclusive access at carrier frequencies of 28 GHz and 73 GHz for each operator, except for the serving mBS (Figure 2).

Another finding related to the utilization of HMSSA strategy is its ability in reducing the number of mBSs to the half and providing a cost-effective solution for enhancing the spectrum utilization and reducing the CO₂ emissions; thus, introducing an environment-friendly wireless communication.

3.2. Average Rate Distributions. In this section, the average rate of all users that belong to the four operators is analyzed based on Monte Carlo simulations. A total of 160 users for each operator are deployed randomly throughout the simulation area. An average of ten users per mBS is assumed in this work. The channel capacity calculation of each UE is performed using Shannon's law illustrated in equation (7). The proposed HMSSA strategy for models 1 and 2 with their spectrum assignments are taken into consideration in this calculation. Figures 6(a) and 6(b) show that the average rate distributions of the proposed strategy for the four operators under models 1 and 2, respectively.

As previously mentioned, the main difference between models 1 and 2 is the allocated spectrum amount at 73 GHz carrier frequency. Such additional amount provides more flexibility to the operators to allocate a part of their spectrum exclusively to enrich the user experience. However, it is shown in Figure 6(b) that the average rate distributions for all operators slightly increases by an average of 7 MHz, 40 MHz, and 13 MHz for the three percentiles of the granted amount of spectrum (5th, 50th, and 95th), respectively. Such observation indicates that granting a large amount of bandwidth to the operator does not necessarily results in an

increasing in the average rate. The reason is that the nature characteristic of mmWave signal could significantly impact the system performance if there is no action taken during the UA process. This confirmed the necessity of presenting an efficient UE-mBS association scheme coupling with the adoption of steerable directional antennas at both mBS and UE to strengthen the viability of mmWave wireless communications.

Figure 7 shows the UE rate enhancement of the proposed semipooled and HMSSA strategy (models 1 and 2) compared to the baseline standalone deployment scenario with respect to different percentile rates (5th, 50th, and 95th) and with some system configurations that are illustrated in Table 3.

Three scenarios are applied for the evaluation procedure, the baseline standalone deployment system with 16 mBSs for each operator. In this scenario, a particular UE that belongs to an operator (i.e., OP1) has the right to associate with only the mBS that belongs to its own operator. While in the semipooled scenario, 16 mBSs are divided into two groups; the first group with eight mBSs operate at 28 GHz carrier frequency and the second group with eight mBSs operate at 73 GHz carrier frequency, where the UEs have the right to associate with mBS that operates at 28 GHz carrier frequency or with mBS that operates at 73 GHz carrier frequency that belongs to its own operator or to its own pair operator based on the highest SINR. In case of HMSSA strategy, UEs can associate with mBS that belongs to its own or to different operator through an integrated option utilizing exclusive, semipooled, and fully pooled spectrum access in hybrid manner.

According to the implementation and evaluation of the above scenarios, it is notably that the proposed semipooled and HMSSA strategy (Model 1) enhances the average rate of the users by more than 143% and 193%, respectively;

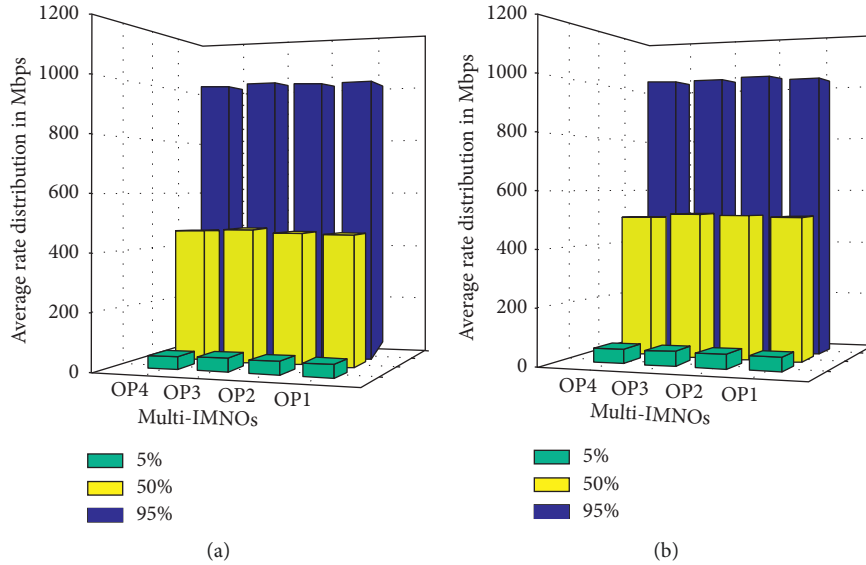


FIGURE 6: Average rate distributions of the four operators utilizing HMSSA strategy: (a) Model 1 and (b) Model 2 with different percentile rates.

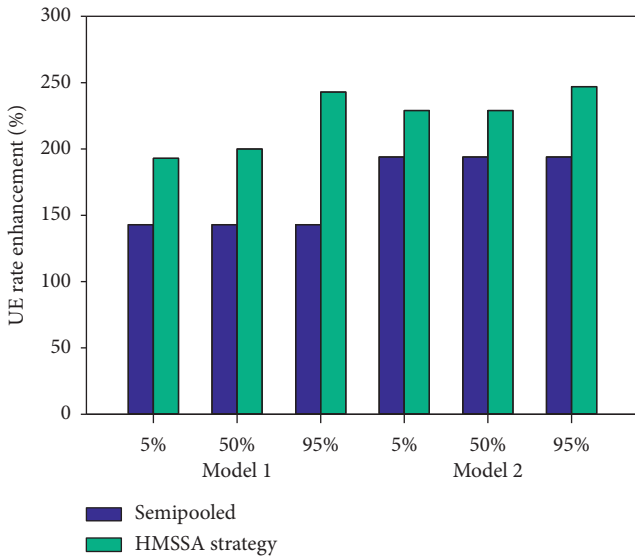


FIGURE 7: Semipooled and HMSSA strategy performance compared to the baseline standalone deployment system (with exclusive access at 28 GHz). X-label indicates the 5th, 50th, and 95th percentiles of the granted amount of spectrum bandwidth under Model 1 and Model 2 configurations.

whereas under (Model 2) configurations, the proposed semipooled and HMSSA strategy enhances the average rate of the users by more than 194% and 229%, respectively. The increase in the UE enhancement rate under Model 2 configurations can be attributed to the extra amount of the allocated bandwidth to the participated operators, specifically in the performance of semipooled (500 MHz at 28 GHz and 750 MHz at 73 GHz for each pair (i.e., OP1 and OP4)), as shown in Table 3.

These observations indicate that the utilization of such hybrid dynamic spectrum access strategy will pave the way

for non-standalone cell deployment with non-standalone licensed spectrum access because of its ultraflexibility and capability that offers an optimal UE-mBS association that helps in maximizing the user experience.

Another important observation is that increasing the amount of allocated spectrum bandwidth at 73 GHz carrier frequency to operate as another exclusive right access for UEs under (Model 2) assumptions does not lead to much improvement in the UE rate. This can be attributed to the fact that UEs tend to associate with mBS that operates under exclusive right access at 28 GHz or 73 GHz which has the highest SINR than mBS that operates under semipooled and fully pooled spectrum access strategy. This UE behavior results in much increasing in the cell load and hence ruins the benefits of such extra amount of the allocated bandwidth at the higher carrier frequency (73 GHz).

To sum up, the reported enhancement in the performance of UE rate can be considered as an encouraging step to enable the success of SSA in 5G mmWave cellular networks with less mBSs density and small amount of spectrum bandwidth compared to the most related works in [7, 11, 12, 15].

3.3. Independence and Fairness Assessment. Assessing the operator’s independence and fairness based on the signal quality (outage probability) and the average rate distributions of particular subscribers that belong to an operator m^{th} is very important to promote the operators to adopt SSA.

Particularly, in this work, characterizing OP1 as an independent operator implies that its performance is not influenced by other operators (e.g., OP2, OP3, and OP4).

Additionally, the term "fairness" is defined as the ability to handle all operators equally or in a manner that all operators are treated without bias.

TABLE 3: Baseline system, semipooled, and HMSSA strategy configurations for UE rate evaluation process.

Scenario	Spectrum access strategy	Carrier frequency	Granted amount of bandwidth	mBS deployment configuration
Baseline	Exclusive access	28 GHz	250 MHz	Standalone deployment
Model 1	Semipooled	28 GHz and 73 GHz	500 MHz at both 28 GHz and 73 GHz for each pair (i.e. OP1 and OP4)	Dual deployment
	HMSSA strategy	28 GHz and 73 GHz	1 GHz at 28 GHz and 73 GHz	Hybrid deployment
Model 2	Semipooled	28 GHz and 73 GHz	500 MHz at 28 GHz and 750 MHz at 73 GHz for each pair (i.e. OP1 and OP4)	Dual deployment
	HMSSA strategy	28 GHz and 73 GHz	1 GHz at 28 GHz and 1.5 GHz 73 GHz	Hybrid deployment

Remark 1. The coverage or average rate probability of user $u^{\text{th},m}$ who associates with operator m^{th} is independent if the coverage or average rate probability of another user does not affect the coverage or average rate probability of user $u^{\text{th},m}$, which can be expressed as follows:

$$\mathbb{P}(\mathbb{P}_{\text{us}}^{m=1\dots M,c}) = \mathbb{P}_{\text{us}}^{1,c} \cdot \mathbb{P}_{\text{us}}^{2,c} \cdot \mathbb{P}_{\text{us}}^{3,c} \cdot \mathbb{P}_{\text{us}}^{4,c} \dots \mathbb{P}_{\text{us}}^{M,c}, \quad (8a)$$

where, $\mathbb{P}(\mathbb{P}_{\text{us}}^{m=1\dots M,c})$ is the coverage or average rate probability of user $u^{\text{th},m}$ that associates with operator m^{th} .

Considering $M = 4$,

$$\mathbb{P}(\mathbb{P}_{\text{us}}^{1,c} \cap \mathbb{P}_{\text{us}}^{2,c} \cap \mathbb{P}_{\text{us}}^{3,c} \cap \mathbb{P}_{\text{us}}^{4,c}) = \mathbb{P}_{\text{us}}^{1,c} \cdot \mathbb{P}_{\text{us}}^{2,c} \cdot \mathbb{P}_{\text{us}}^{3,c} \cdot \mathbb{P}_{\text{us}}^{4,c}. \quad (8b)$$

More specifically, either coverage or average rate probability of any operator (OP1 and OP2 as an example) is independent if and only if

$$\mathbb{P}\left(\frac{\mathbb{P}_{\text{us}}^{2,c}}{\mathbb{P}_{\text{us}}^{1,c}}\right) = \left(\frac{\mathbb{P}(\mathbb{P}_{\text{us}}^{1,c} \cap \mathbb{P}_{\text{us}}^{2,c})}{\mathbb{P}_{\text{us}}^{1,c}}\right) = \mathbb{P}_{\text{us}}^{2,c}. \quad (8c)$$

This condition can be applied for other operators to assure their independence.

By substituting the coverage probability of each user $u^{\text{th},m}$ in equation (8b),

$$\begin{aligned} \mathbb{P}(\mathbf{x}_{\text{us}}^{1,c}) \cap \mathbb{P}(\mathbf{x}_{\text{us}}^{2,c}) \cap \mathbb{P}(\mathbf{x}_{\text{us}}^{3,c}) \cap \mathbb{P}(\mathbf{x}_{\text{us}}^{4,c}) &= (\mathbf{x}_{\text{us}}^{1,c}) \cdot \mathbb{P}(\mathbf{x}_{\text{us}}^{2,c}) \\ &\quad \cdot \mathbb{P}(\mathbf{x}_{\text{us}}^{3,c}) \cdot \mathbb{P}(\mathbf{x}_{\text{us}}^{4,c}). \end{aligned} \quad (8d)$$

Recall equation (5). The coverage probability of each user $u^{\text{th},m}$ as a function of SINR entirely depends on the received signal power and the amount of interference from other adjacent mBSs that operate at the same band. User orientation in terms of the deployed mBS and the spectrum access strategy are key components in determining the received signal power and the amount of interference, respectively.

As $u^{\text{th},m}$ can only associate with the tagged mBS that offers a high SINR regardless of which operator it belongs to, in order to maximize its channel capacity. Moreover, four operators are considered in this study ($M = 4$); each operator has four mBSs. Each mBS has three different spectrum assignments (exclusive at 28 GHz, semipooled at 73 GHz, and fully pooled at 73 GHz) in Model 1 and (exclusive at 28 GHz, exclusive at 73 GHz, and fully pooled at 73 GHz) in Model 2. Therefore, equation (7) can be rewritten as

$$\begin{aligned} R_{\text{us}}^{m,c} &= \Phi_{\text{us}}^{m,c} \times \left(\frac{W^{m,c}}{u_{\text{sth}}^{m,c}}\right) \times \log_2\left(1 + \max\left(\max\left(\mathbf{x}_{\text{us}}^{1,c=1,2,3}\right) \cup \right. \right. \\ &\quad \left. \left. \cdot \max\left(\mathbf{x}_{\text{us}}^{2,c=1,2,3}\right) \cup \max\left(\mathbf{x}_{\text{us}}^{3,c=1,2,3}\right) \cup \max\left(\mathbf{x}_{\text{us}}^{4,c=1,2,3}\right)\right)\right), \end{aligned} \quad (9)$$

where $c = 1, 2, 3$ denotes the spectrum assignments of each mBS. On the basis of equation (9), the average rate of each user depends on the SINR value regardless of which operator it belongs. Therefore, the utilization of the proposed strategy achieves a high degree of independence in terms of both performance metrics (i.e., coverage or average rate probability).

In terms of fairness, standard deviation formula is utilized to assess the differences among the operators that share the spectrum in terms of average rate distributions.

Remark 2. The average rate percentages of all operators are relatively close to one another. The small margin in the average rate probability among all operators indicates that the resources are evenly allocated to the users regardless of which operator the users belong to.

The standard deviation of the average rate of a set of operators is expressed as follows:

$$\text{SD}^{\text{ALL}} = \sqrt{\frac{\sum |\text{Avg}R^m - \mu|^2}{m}}, \quad (10)$$

where SD^{ALL} denotes the standard deviation of the average rate of M operators. Without loss of generality, $\text{Avg}R^m$ denotes the average rate of operator m^{th} . μ is the mean of the average rate values of M operators, which is represented by summing up all the average rates of a set of operators divided by the number of operators M .

As shown in Table 4, the proposed HMSSA strategy is successful in terms of equity in resource allocation, in which the maximum margin of the average rate does not exceed 6.4727 Mbps. The HMSSA strategy margin in terms of the exclusive or semipooled access and fully pooled access, along with their percentages can be ignored in comparison with the high data rate experienced by the users belonging to the operators. Thus, operators are encouraged to rely on such strategy, which has proven its proportional fairness in terms of resource allocation. The small margin results from the user positioning in terms of the deployed mBS and not from the rules of the proposed HMSSA strategy, in which UEs that

TABLE 4: Margin percentage and standard deviation of the proposed HMSSA strategy (Model 1 and Model 2).

HMSSA configurations	Percentiles (%)	HMSSA margin in terms of		SD ^{ALL} (Mbps)	Average rate (Mbps)			
		Fully pooled access (%)	Exclusive or semipooled access (%)		OP1	OP2	OP3	OP4
Model 1	95	0.845	1.691	4.0169	1005.5	1004.4	1013.1	1005.5
	50	2.548	5.097	6.3713	457	462	472.3	463.5
	5	7.662	15.2	1.9155	44.3	45.8	47.7	43.3
Model 2	95	1.362	2.366	6.4727	1010.6	1026.3	1019.7	1017.5
	50	2.082	4.165	5.2066	506.2	509.9	513.9	501.7
	5	1.876	3.752	0.4690	50.1	51.2	50.6	50.9

belong to the different operators are deployed randomly and independently. Accordingly, the competition among multiple operators in terms of service delivery will be conducted in a proportionally fair manner with the existence of the hybrid SSA.

4. Conclusions

In this study, we investigate the implementation of a flexible HMSSA strategy by analyzing various practical aspects, such as spectrum access strategies, various rate percentiles, and two mmWave frequency bands with different characteristics and spectrum bandwidth. An optimization framework was developed to enable operators to harvest the gains from several considerations, such as hybrid spectrum integration, resource sharing strategy, as well as user-mBS association. Moreover, a detailed analytical and discussion is presented to assess independence and fairness among operators under the proposed HMSSA strategy assumptions. The numerical results show that the integration of a hybrid spectrum (i.e., exclusive, semipooled, and fully pooled) strategy can provide a considerable solution to overcome mutual interference issues, thereby reducing outage probability to zero with (SINR > 3 dB) and the number of mBSs to the half providing capital expenditure (CapEx) and operating expenditure (OpEx) savings. Furthermore, compared with exclusive access, the utilization of the proposed strategy is generally beneficial for guaranteeing an acceptable level of operator's independence and fair spectrum usage and maximizing the UE rate more than two folds. Moreover, utilizing such strategy aids in enabling a rapid creation of new wireless applications in a cost-effective manner. In future studies, we will expand these investigations to more complex scenarios, considering the adoption of spectrum access system and licensed shared access spectrum sharing models. UE-mBS association advancement will be part of the future work to improve mBS selection for enabling the SSA to meet the boldest 5G constraints.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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