

## Hybrid multi-independent mmWave MNOs assessment utilising spectrum sharing paradigm for 5G networks

Mothana L. Attiah<sup>1</sup>, A. A. Md Isa<sup>2</sup>, Zahriladha Zakaria<sup>\*3</sup>, M. K. Abdulhameed<sup>4</sup>,  
Mowafak K. Mohsen<sup>5</sup>, Ahmed M. Dinar<sup>6</sup>

<sup>1-6</sup>Centre for Telecommunication Research and Innovation (CeTRI),  
Faculty of Electronic and Computer Engineering (FKeKK),  
Universiti Teknikal Malaysia Melaka (UTeM), Malaysia

<sup>1</sup>Department of Computer Engineering, Electrical Engineering Technical College,  
Middle Technical University, Baghdad, Iraq

\*Corresponding author, e-mail: mothana.utem@gmail.com<sup>1</sup>, zahriladha@utem.edu.my<sup>3</sup>

### Abstract

*Spectrum sharing paradigm (SSP) has recently emerged as an attractive solution to provide capital expenditure (CapEx) and operating expenditure (OpEx) savings and to enhance spectrum utilization (SU). However, practical issues concerning the implementation of such paradigm are rarely addressed (e.g., mutual interference, fairness, and mmWave base station density). Therefore, in this paper, we proposed ultra-reliable and proportionally fair hybrid spectrum sharing access strategy that aims to address the aforementioned aspects as a function of coverage probability (CP), average rate distributions (ARD), and the number of mmWave base stations (mBSs). In this strategy, the spectrum is sliced into three parts (exclusive, semi-pooled, and fully pooled). A typical user that belongs to certain operator has the right to occupy a part of the spectrum available in the high and low frequencies (28 and 73 GHz) based on an adaptive multi-state mmWave cell selection scheme (AMMC-S) which associates the user with the tagged mBS that offers a highest SINR to maintain more reliable connection and enrich the user experience. Numerical results show that significant improvement in terms of ARD, CP, fairness among operators, and maintain an acceptable level of mBSs density.*

**Keywords:** hybrid mmWave spectrum sharing access (HMSSA), multi-IMNOs, 5G

Copyright © 2019 Universitas Ahmad Dahlan. All rights reserved.

### 1. Introduction

The expected massive growth in the diverse innovative technologies and services in the future cellular communication era 5G such as Internet of Things (IoT), autonomous driving, augmented reality (AR), healthcare and virtual reality (VR) are deemed to add other challenges on stakeholders (ISPs, MNOs, Telcos) to meet the requirements of such bandwidth-hungry applications [1]. On the other hand, the inefficient spectrum usage (e.g., granting large amount of the spectrum exclusively to single operator) [2], along with the scarcity of available microwave spectrum [3], make it very difficult to accommodate these requirements unless there are serious steps to optimize the spectrum utilization and add a new spectrum to be adopted in (5G) system. Given the excellent opportunities of mmWave frequencies such as a massive amount of spectrum bandwidth as well as the super interference-reduction merits (high directionality) [4–6], spectrum sharing paradigm (SSP) can be a possible option in fifth generation cellular networks (5G) [7]. Although, spectrum sharing among multiple independent mobile network operators (multi-IMNOs) has a great opportunity to reduce the costs and improve the efficiency of the spectrum usage, attaining a considerable enhancement in spectrum efficiency without sacrificing the merits that are associated with the static spectrum allocation remains a major challenge [8]. Furthermore, mutual interference is another issue paired with SSP due to multi-IMNOs share the same spectrum band orthogonally [9].

Therefore, the presence of Ultra-flexible SSP that considers the aforementioned challenges is very necessary to achieve the desired end. In this context, a few research activities have been conducted to study the feasibility of SSP in the mmWave network [3], [9–16]. Various use cases have been considered to mimic the expected realistic environment in the future SSP. In particular, Boccardi et al. [3] have addressed the technical

enablers of SSP (e.g., supporting architecture, the way of coordination, and new network functionalities). This study revealed that utilizing of SSP could enhance the spectrum utilization as compared to the conventional spectrum allocation (closed access). In [9], modeling infrastructure sharing have been presented, however, two mmWave cellular operators with two scenarios fixed individual network densities (FID) and fixed combined network density (FCD). The results show that infrastructure and spectrum sharing is more convenient for high-rate applications rather than low-rate application. In [10], a coordination context-based scheme has been proposed to alleviate the mutual interference issue that arose from sharing the spectrum among multi-IMNOs which deployed in the overlapping area. The feasibility of uncoordinated sharing the spectrum among multi-IMNOs has been studied in [11–15].

These studies demonstrated the effectiveness of SSP form both the technical and economical point of view. The economic implication of SSP is mainly addressed in [16], and the results clarify that resource sharing is beneficial for MNOs that support mmWave and microwave cellular networks. However, this feature is not necessarily translated to significantly maximise their own profits but may only encourage additional subscribers to occupy the shared spectrum. Furthermore, mandated sharing increases the low-end NSP profits and may encourage them to stay in the market, thereby improving consumer surplus relative to a monopoly. In this article, we extend the prior studies [3], [9–16], and our work in [17] by considering new assumptions with regard to the use of hybrid mmWave spectrum sharing access (HMSSA) strategy, different path loss models (commonly used), network planning and enhancing the flexibility of the operators with a low number of mBSs. We also suggest two access models to be adopted by the multi-IMNOs based on two dissimilar spectrum bandwidth amounts.

## 2. Research Method

In this section, our framework is divided into four key parts to accurately simulate and apply the baseline and the proposed HMSSA strategy configurations as summarised below:

### 2.1. Network Model

To serve a specified geographical area, we consider two tiers of multi-IMNOs given by  $M$ . Each operator  $m^{th}$  has two spectrum bandwidths based on two carrier frequencies (28 and 73 GHz) given by  $c$ . Without loss of generality, let  $W_{m,c}$  denotes the total spectrum that is allocated to each operator  $m^{th}$ . Let  $J_m$  be a set of mBSs of an operator  $m^{th}$  and  $J = J_1 \cup J_2 \dots \cup J_m$  be the set of all mBSs in the network. However, all operators have their own mBSs  $J_m$  that can operate optionally at the two aforementioned mmWave carrier frequencies. 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 UEs, such that the simulation area is 1.2 Km×1.2 Km. Each has the right of granting exclusively a part of its allocated spectrum  $W_{m,\ell}$  for the users that belong to their operator in the lower mmWave band (28 GHz), and semi-orthogonal or fully-orthogonal sharing a part of its allocated spectrum  $W_{m,h}$  to the users that belong to that operator or to another operator in the higher mmWave band (73 GHz). Let  $U$  denotes the set of outdoor UEs and  $U = U_1 \cup U_2 \dots \cup U_m$ , where,  $U_m$  be a set of users of an operator  $m^{th}$ . Each  $u^{th,m}$  is served by a set of mBS  $J_m$  that belongs to the same or different operator depending on the spectrum allocation strategy and the link quality signal. For a given association, we utilise our proposed scheme in [18], abbreviated (AMMC-S) to adaptively select the serving mBS that offers a link with high  $SINR$ . All mBSs that are owned by MNOs and their UEs are assumed to be powered by multi-antenna systems.

### 2.2. Mathematical Model

We consider two types of mathematical models: the models that are related to basic mobile communications and those that are related to the mmWave communication system. They are rewritten and developed to optimally meet the baseline and the proposed strategy requirements. To calculate the received signal power at the receiving antenna, we consider the commonly used close-in reference distance path loss model [19, 20].

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

where  $PL(d_{uj})^{m,c}$  denotes the average path loss in dB for a specific user/terminal  $u^{th,m}$  with respect to  $j^{th,m}$  mBS that operates at mmWave carrier frequency  $c$  and owned by the operator  $m^{th}$ .

The separation distance is  $d_{uj}$  in meters.  $d_o$  denotes the close-in free space reference distance (1 m),  $PL_{fs}(d_o)$  denotes the close-interference free space path loss in dB as identified in (2) [20],  $\gamma$  denotes the average path loss exponent and  $x_\sigma$  denotes zero mean Gaussian random variable with  $\sigma$  as a standard deviation in (dB) given that 10 dB shadowing margin is used in our work. Finally,  $\gamma$  denotes the path loss exponent in dB (for 28GHz=3.4 and 73GHz=3.3).

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

where  $\lambda$  stands for the wavelength of the carrier frequency in mm (10.71 and 4.106) for 28GHz and 73 GHz respectively [21, 22]. Typically, to calculate the average received signal power at the receiver, we firstly compute the path loss attenuation based on (1) and then execute (3) as follows [23]:

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

To meet the assumptions of the utilisation of hybrid mBS deployment, we rewrite (3) again as expressed below:

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

where  $Pr_{uj}^{m,c}$  and  $P_t^{m,c}$  are the received and transmitted power of mBS  $j^{th,m}$ , respectively, which is owned by the operator  $m^{th}$  and operated at mmWave carrier frequency  $c$ ;  $G_t^{m,c}$  and  $G_r^{m,c}$  are the linear gains of the transmitter and the receiver antennas in dBi, respectively;  $PL_{uj}^{m,c}$  is the average path loss in dB.

To characterise the performance of each operator of the multi-IMNOs, we consider the *SINR* to assess the outage probability. We assume that the threshold value of the *SINR* of a user  $u^{th,m}$  served by an operator  $m^{th}$  is in an outage if the *SINR* value is below than zero. For example, a user  $u^{th,m}$  associates with mBS  $j^{th,m}$  that is owned by that operator or different operator  $m^{th}$  who shared or exclusively granted a certain amount of spectrum in the carrier frequency  $c$  of either 28 GHz or 73 GHz. Then, the *SINR* of user  $u^{th,m}$  can be calculated by using (5) [24].

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

where  $\mathfrak{S}_{uj}^{m,c}$  denotes the *SINR*;  $\sum_{n=1}^N I_{uj}^{m,c}$  denotes the aggregated interference received by the receiver  $u^{th,m}$  from all neighbouring mBSs that operate at the same frequency band and owned by that operator or different operator  $m^{th}$  except the serving mBS  $j^{th,m}$ . Specifically, we assume that only a single beam comes from mBS  $j^{th,m}$  that interferes the receiver  $u^{th,m}$ ,  $\eta^{m,c}$  denotes the additive white noise power of the operator  $m^{th}$  for a carrier frequency  $c$  and is given by [23]:

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

where  $10 \times \log_{10}(KT_{sys})$  for a given system temperature (17 °C) equal to -174 dBm/Hz;  $NF^{m,c}$  denotes the noise figure with a value of 6 dB. The calculation of  $\mathfrak{S}_{uj}^{m,c}$  is made to provide further user channel capacity calculation using Shannon capacity theory as shown in (7) [24, 25]:

$$\mathbb{R}_{uj}^{m,c} = \phi_j^{m,c} \times \left( \frac{W^{m,c}}{U_{jth}} \right) \times \log_2(1 + \mathfrak{S}_{uj}^{m,c}) \quad (7)$$

where  $\Phi_j^{m,c}$  denotes to the number of antenna elements in the connected mBS  $j^{th,m}$ ;  $W_{m,c}$  denotes the total amount of spectrum bandwidth of  $m^{th}$ .  $\mathbb{R}_{u_j}^{m,c}$  denotes the channel capacity of  $u^{th,m}$ ,  $U_{j^{th,m}}$  denotes the number of users that are connected to the tagged  $j^{th,m}$ .

### 2.3. HMSSA Strategy

We address the most important considerations of the proposed (HMSSA) strategy and its models meticulously. Four multi-IMNOs are considered which are distributed throughout the simulation area of 1.2 km×1.2 km following the grid-based cell deployment topology. We propose two access models to be adopted by the aforementioned operators. Each  $m^{th}$  grants exclusively a certain amount of the spectrum  $W_{m,c}$  supplied by a certain carrier frequency  $c$  to its subscribers or shares it with other operator’s subscriber, as detailed below:

#### 2.3.1. Model 1

We assume that the total amount of spectrum ( $W_{m,\ell} = W_{m,h} = 1$  GHz) at the low and high frequencies (28 and 73 GHz) respectively. In this model, the spectrum  $W_{m,\ell}$  is sliced evenly into four parts, each with 250 MHz. Each operator  $m^{th}$  grants exclusive right of 250 MHz of the available spectrum supplied by the low carrier frequency of 28 GHz to only its subscribers  $u^{th,m}$  while avoiding co-channel interference with other adjacent operators. Meanwhile, in the higher carrier frequency 73 GHz, the spectrum  $W_{m,h}$  is divided into two parts, each with 500 MHz. The first part (500 MHz) is pooled/shared among all operators. The second part (500 MHz) is sliced into two parts, and each part is assigned as semi-pooled/shared (S-P/S) to only two operators. 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.

#### 2.3.2. Model 2

We assume that we have two different sets of spectra:  $W_{m,\ell} = 1$ GHz at 28 GHz and  $W_{m,h} = 1.5$ GHz at 73 GHz. In this model, the spectrum assignment is similar to that in model 1 for the lower mmWave frequency band of 28 GHz. However, the allocated amount of the 1 GHz spectrum at the carrier frequency of 73 GHz is available for exclusive access. Each operator  $m^{th}$  grants exclusive rights of 250 MHz of the available spectrum for only its subscribers  $u^{th,m}$ . In this assignment, the co-channel interference is non-existent. The remaining amount of the 1.5 GHz spectrum at 73 GHz (500 MHz) is shared among the four operators as depicted in Figure 2.

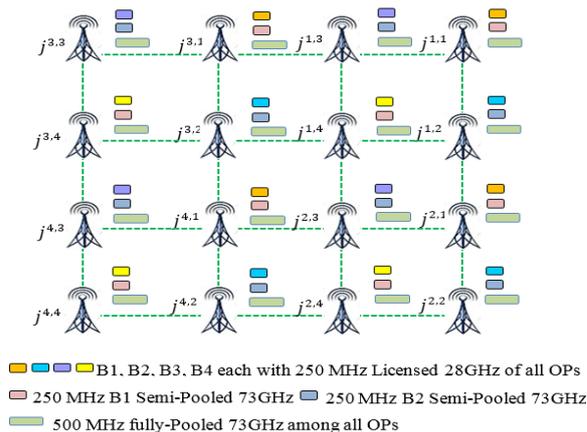


Figure 1. HMSSA Model 1

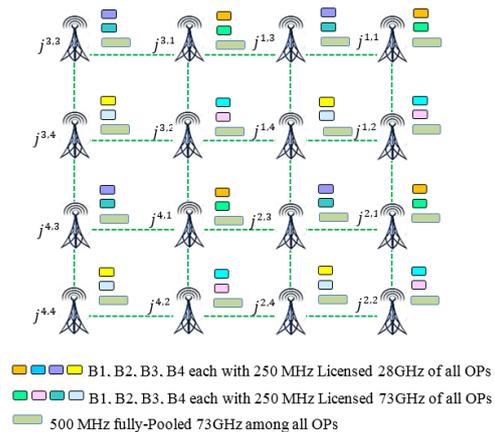


Figure 2. HMSSA Model 2

### 2.4. UE-MmWave BSs Association (AHMMC–S) Scheme

In the proposed access strategy under model 1, the UEs/terminals  $u^{th,m}$  that subscribe to the operator  $m^{th}$  have the right to associate with mBS  $j^{th,m}$  that belongs to that operator or to different operator share the same frequency band depending on the quality of the signal that is

offered by such mBS. More precisely, there are three options available to the users of OP1 as an example can be summarised as follows:

- a. UEs of OP1 can associate with mBS of OP1 that offers exclusive right access of 250 MHz at 28 GHz and the same for the users that belong to other operators.
- b. UEs of OP1 can associate with mBS that belongs to the same operator or to OP4 that offers semi-pooled access of 250 MHz at 73 GHz and vice versa for UEs of OP4.
- c. UEs of OP1 can associate with mBS that belongs to OP1, OP2, OP3 or OP4 which offers a fully shared/pooled access of 500 MHz of the spectrum. All the aforementioned options are same for the users that belong to other operators unless the second options where the UEs of OP2 can associate with mBS that belongs to the same operator or to OP3 and vice versa.

In model 2, the UEs that subscribe to the operator  $m^{th}$  have the right to associate with mBS  $j^{th,m}$  that belongs to that operator or to a different operator who shared the same frequency band based on the same constraints and options in model 1 unless the second option, where UEs of (OP1) can only associate with mBS OP4 that offers an exclusive rights access of 250 MHz at 73 GHz, and vice versa. Whereas, UEs of OP2 can only associate with mBS of OP3 under the same assignment and carrier frequency and vice versa. In this case, the interference will be lower than those in model 1 that utilises semi-pooled spectrum access. The user and mmWave cell association decision are performed by using the proposed (AMMC-S) scheme, which relies on providing an optimal cell selection based on the offered signal quality as a function of  $SINR$ .

### 3. Results and Analysis

In this section, we numerically evaluate the performance of the proposed HMSSA strategy in a typical mmWave scenario that supports two hybrid access models based on the distribution and allocation spectrum. Two key performance metrics (outage probability as a function of  $SINR$  and average rate distributions) are considered to assess the effectiveness of the proposed strategy along with the two aforementioned models. The related assumptions and simulation parameters are listed in Table 1.

Table 1. Simulation Parameter Settings

Parameters	Settings
MmWave Base Station Layout	Grid-based Cell Deployment
MmWave Base Station Density	16
Number of Operator	4
UE Layout	Uniform random distribution
UE Density	160 Users
Area of Simulation	1.2 Km×1.2 Km
Inter-Site Distance (ISD)	300 m
mBS Carrier Frequency	28GHz and 73GHz
mBS Transmit Power	30 dBm
Variant of White Gaussian Noise	-174 dBm/Hz
mBS Bandwidth	Model 1:1GHz for 28GHz and 73GHz Model 2:1GHz for 28GHz and 1.5GHz for 73GHz

#### 3.1. SINR Distributions

As signal-to-interference plus noise ratio represents a key system interference indicator, it is essential to study its impact on 5G mmWave networks, especially with the utilization of SSP and with the two models (model 1 and model 2) as detailed in the next following subsections.

##### 3.1.1. HMSSA Results and Discussion (Model 1)

Figures 3 (a), (b) and (c) shows the outage probability of OP1, OP2, OP3 and OP4 based on different allocation bandwidth percentiles (5%, 50%, and 95%) utilising HMSSA (model 1) configurations. Such  $SINR$  distributions are averaged over a sufficient number of iterations to achieve the desired accuracy. A typical user  $u^{th,m}$  which associates with mBS  $j^{th,m}$  that belongs to the same operator based on the exclusive right access (250 MHz) at 28 GHz carrier frequency has higher  $SINR$  (lower outage) than the semi-pooled and fully-pooled spectrum access at 73 GHz carrier frequency. The reason behind that, such semi-pooled and

fully-pooled spectrum accesses are semi-open or fully open access, hence, the amount of interference is larger than that in the exclusive right spectrum assignment. The number of adjacent mBSs that are operated by the two aforementioned access strategies (semi-pooled and fully pooled) are 7 and 15 respectively; by contrast, only 3 mBSs operate in the exclusive right access except for the serving mBS, as shown in Figure 1. However, in general, the location of a user  $u^{th,m}$  in terms of mBS  $j^{th,m}$  plays a dominant role in reducing the outage probability. We found that the *SINR* distribution of the fully pooled spectrum access outperforms that in the semi-pooled spectrum access in some iterations. This will happen when the users are closer to mBS  $j^{th,m}$  that belongs to other operator in which only one choice for those users to associate with such mBS  $j^{th,m}$ . For instance, a user  $u^{th,1}$  that subscribes to OP1 that is located extremely close to mBSs  $j^{th,2}$  and  $j^{th,3}$  which are owned by OP2 and OP3, will only have one choice to associate with one of the two mBS  $j^{th,2}$  and  $j^{th,3}$  that offer a fully-pooled spectrum access. In our proposed HMSSA strategy under model 1 extra 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 reduces significantly with *SINR* more than 3 dB of the cell-edge users, which outperforms the state of arts in [3], [9–12]. 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 and the number of mBSs can be decreased because only 16 mBSs are needed to be deployed through 1.2 km×1.2 km with good coverage. The outage probability percentages of the proposed (HMSSA) of OP1, OP2, OP3 and OP4 are zero (0%), as shown in Figures 3 (a), (b) and (c).

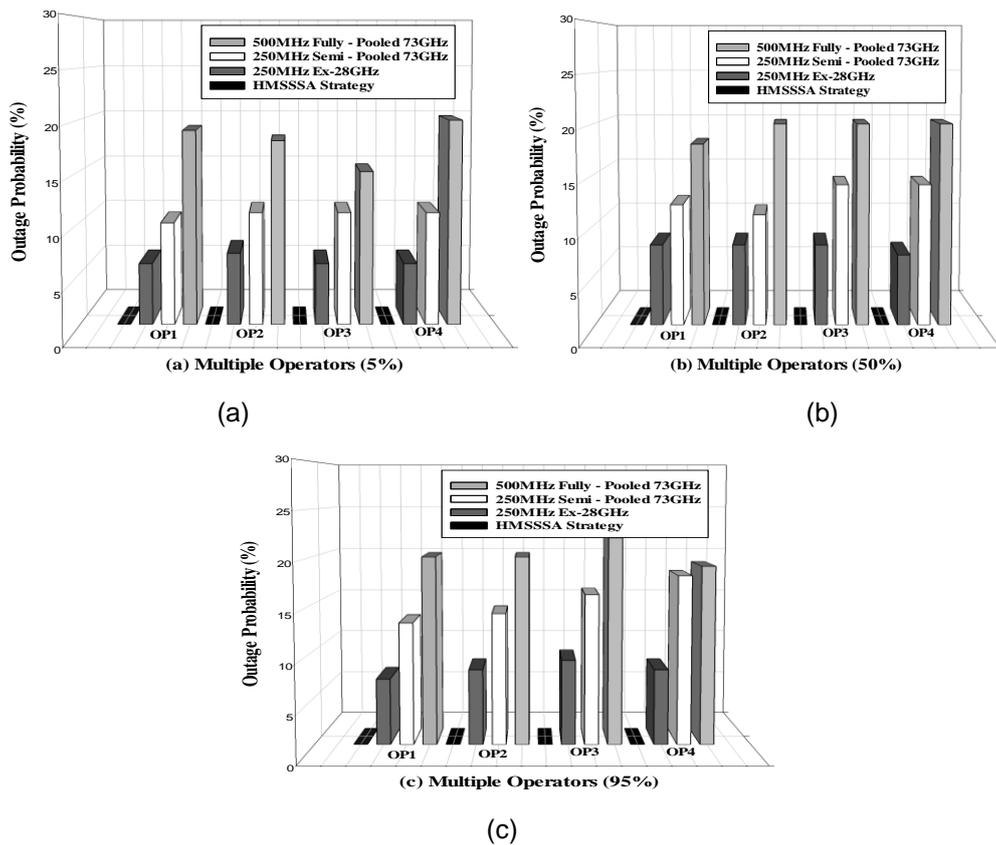


Figure 3. Outage probability percentage of different percentiles (a) 5% (b) 50% (c) 95% for all operators (model 1)

### 3.1.2. HMSSA Results and Discussion (Model 2)

Model 2 is similar to model 1. However, the allocated amount of the spectrum in model 1 and model 2 is different. Additionally, in model 2 each user can be associated with any

mBSs belong to the same operator or two different operators based on one of the two options, either based on exclusive right access of 250 MHz at 28GHz and fully pooled access of 500 MHz at 73 GHz carrier frequency or exclusive right access of 250 MHz at 73 GHz and fully shared/pooled access of 500 MHz of the spectrum at 73 GHz carrier frequency. Such restrictions in model 2 helps to achieve an improvement in terms of the outage probability of the semi-pooled spectrum access. The *SINR* distributions of the proposed strategy of all operators are kept zero (0%) as depicted in Figure 4 (a), (b) and (c), with some improvement in the *SINR* value (>6dB). This improvement widens the gap with other spectrum access strategies (exclusive right, fully-pooled) adding 3dB to the cell-edge users (as compared to model 1). The reason is that the extra amount of spectrum at 73 GHz reduces the interference between the mBSs owing to the reduction in the number of adjacent mBSs that operate in the same bands. The number of adjacent mBSs that are operated by the fully pooled access strategy is 15, whereas only 3 adjacent mBSs are operated by exclusive rights access at the two carrier frequencies of 28 and 73 GHz for each operator except the serving mBS, as depicted in Figure 2.

After extensive iteration, the user location plays an important role in shaping the system performance. Furthermore, network planning is a key point in reducing the mutual interference that garbles both transmitters' signals that be a major reason to impede the process of spectrum sharing among multi-IMNOs. Additionally, proportional fairness seems very clear in both CP and ADR. This another strong point provided by (HMSSA) strategy wick encourages multi-MNOs to rely on such a strategy that ensures the competition between them to be in a fair manner.

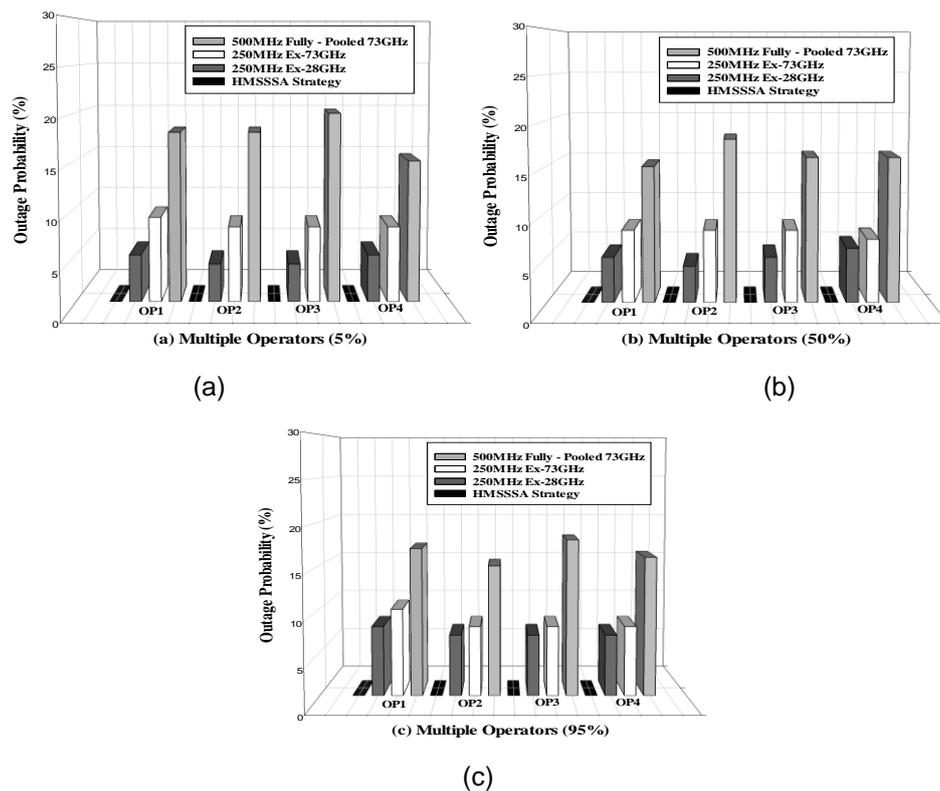


Figure 4. Outage probability percentage of different percentiles (a) 5% (b) 50% (c) 95% for all operators (model 2)

### 3.2. Average Rate Distributions

In this section, we analyse the average rate of the users that belong to the four operators based on Monte Carlo simulations. Since 160 users for each operator are deployed randomly throughout the simulation area. We assume that there are on average ten users per mBS. By using Shannon's law illustrated in (7), we calculate the average rate of each

UE based on (exclusive right at 28 GHz, semi-pooled at 73 GHz, fully pooled at 73 GHz and our proposed strategy (HMSSA)) for model 1 and (exclusive right at 28 GHz, exclusive right at 73 GHz, fully pooled and our proposed strategy (HMSSA)) for model 2.

Figure 5 (a) and (b) shows the average rate of the four operators with the utilisation of (HMSSA) strategy under model 1 and model 2 configurations. The main difference between model 1 and model 2 is the allocated amount of the spectrum at 73 GHz carrier frequency. Such extra amount adds more flexibility to each operator to allocate exclusively a part of the total amount of the spectrum bandwidth to enrich the user experience. As can be observed from Figure 5 (a) and (b), the average rate distributions for all operators are slightly increased by an average 7 MHz, 40 MHz, and 13 MHz for the three rate percentiles (5<sup>th</sup>, 50<sup>th</sup>, and 95<sup>th</sup>) respectively. This indicates that granting a large amount of bandwidth to the operator does not necessarily lead to much more increase in the average rate due to the nature merits of the mmWave frequencies.

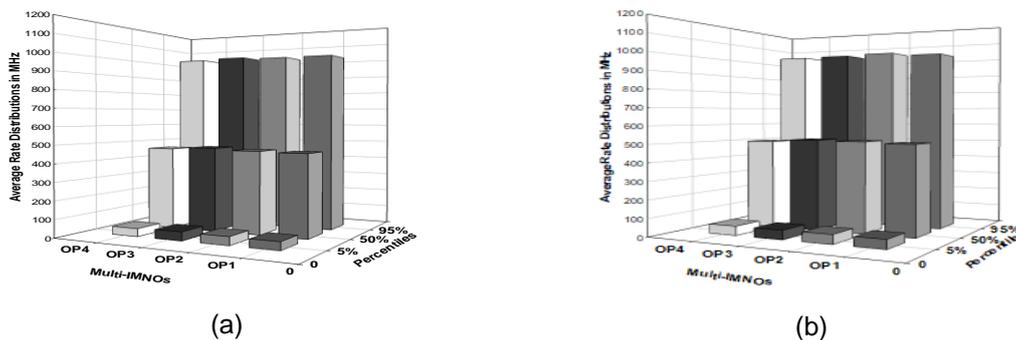


Figure 5. Average rate distribution of four operators utilising our proposed (HMSSA) strategy with different percentiles (a) model 1 and (b) model 2

#### 4. Conclusion

In this article, we investigate the implementation of a flexible hybrid mmWave spectrum sharing access (HMSSA) strategy by analysing different practical aspects. More precisely, different spectrum access strategies, various rate percentiles, two mmWave frequency bands with different characteristics and dissimilar spectrum bandwidth amounts. The numerical results show that the integration of a hybrid spectrum (exclusive, semi-pooled and fully pooled) strategy can effectively overcome the mutual interference issues, hence, reducing the outage probability and optimising the number of mBSs. Furthermore, the utilization of such a paradigm is generally beneficial for guaranteeing an efficient and fair usage of the spectrum and maximizing the UEs rate more than three folds as compared with the exclusive rights. Moreover, it enables the rapid creation of new wireless applications in a cost-effective manner. For future work, we will expand these investigations to more complex scenarios to assess the cooperated operators independent as an encouraging step to the MNOs to rely on SSA.

#### Acknowledgments

The authors gratefully acknowledge UTeM Zamalah Scheme, Universiti Teknikal Malaysia Melaka (UTeM), and the Center for Research and Innovation Management (CRIM), Center of Excellence, Universiti Teknikal Malaysia Melaka (UTeM).

#### References

- [1] Rappaport TS, Sun S, Mayzus R, et al. Millimeter wave mobile communications for 5G cellular: It will work!. *IEEE access*. 2013;1(1):335-349.
- [2] NTIA (2003). U.S. frequency allocations. [online]. Available: <http://www.ntia.doc.gov/files/ntia/publications/2003-allochrt.pdf>.
- [3] Boccardi F, Shokri-Ghadikolaei H, Fodor G, Erkip E, Fischione C, Kountouris M, Popovski P, Zorzi M. Spectrum pooling in mmwave networks: Opportunities, challenges, and enablers. *IEEE Communications Magazine*. 2016;54(11):33-39.

- [4] Abdulhameed MK, Isa MM, Zakaria Z, Mohsin MK, Attiah ML. Controlling The Radiation Pattern of Patch Antenna Using Switchable EBG. *TELKOMNIKA Telecommunication Computing Electronics and Control*. 2018;16(5): 2014-2022.
- [5] Mohsen MK, Isa MS, Isa AA, Zakaria Z, Abdulhameed MK, Attiah ML. Control radiation pattern for half width Microstrip leaky wave antenna by using PIN Diodes. *International Journal of Electrical and Computer Engineering (IJECE)*. 2018; 8(5): 2959-2966.
- [6] MK Abdulhameed, MSM Isa, Z.Zakaria, MK Mohsin, Attiah ML. Mushroom-Like EBG to Improve Patch Antenna Performance For C-Band Satellite Application. *International Journal of Electrical and Computer Engineering (IJECE)*. 2018; 8(5): 1-8.
- [7] Park J, Andrews JG, Heath RW. Inter-Operator Base Station Coordination in Spectrum-Shared Millimeter Wave Cellular Networks. to appear in *IEEE Transactions Cognitive Communication and Networking*, 2018.1–16.
- [8] Pandit S, Singh G. *Spectrum Sharing in Cognitive Radio Networks*. Gewerbestrasse, Cham, Switzerland: Springer Int. Publ. 2017: 1-240.
- [9] Jurdi R, Gupta AK, Andrews JG, Heath RW. Modeling Infrastructure Sharing in mmWave Networks with Shared Spectrum Licenses. *IEEE Transactions Cognitive Communication and Networking*, 2018; 4(2): 328-343.
- [10] Li G, Irnich T, Shi C. *Coordination context-based spectrum sharing for 5G millimeter-wave networks*. 2014 9<sup>th</sup> International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM). Oulu, Finland. 2014: 32–38.
- [11] Gupta AK, Andrews JG, Heath Jr RW. On the Feasibility of Sharing Spectrum Licenses in mmWave Cellular Systems. *IEEE Transactions on Communications*.2016; 64(9):3981-3995.
- [12] Rebato M, Mezzavilla M, Rangan S, Zorzi M. *Resource Sharing in 5G mmWave Cellular Networks*. 2016 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS). San Francisco. 2016: 271-276.
- [13] Shokri-Ghadikolaei H, Boccardi F, Fischione C, Fodor G, Zorzi M. Spectrum sharing in mmWave cellular networks via cell association, coordination, and beamforming. *IEEE Journal on Selected Areas in Communications*. 2016; 34(11): 2902-2917.
- [14] Rebato M, Boccardi F, Mezzavilla M, Rangan S, Zorzi M. *Hybrid spectrum access for mmW ave networks*. 2016 Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net). Vilanova i la Geltru. 2016: 1-7.
- [15] Rebato M, Boccardi F, Mezzavilla M, Rangan S, Zorzi M. Hybrid spectrum sharing in mmwave cellular networks. *IEEE Transactions on Cognitive Communications and Networking*. 2017; 3(2): 155-168.
- [16] Fund F, Shahsavari S, Panwar SS, Erkip E, Rangan S. *Resource sharing among mmWave cellular service providers in a vertically differentiated duopoly*. 2017 IEEE International Conference on Communications (ICC). Paris. 2017:1-7.
- [17] Attiah ML, Isa AA, Zakaria Z, Ismail M, Nordin R, Abdullah NF. Coverage Probability Optimization Utilizing Flexible Hybrid mmWave Spectrum Slicing-Sharing Access Strategy for 5G Cellular Systems. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*. 2018; 10(2): 91-98.
- [18] Attiah ML, Isa AA, Zakaria Z, Abdullah NF, Ismail M, Nordin R. Adaptive Multi-State Millimeter Wave Cell Selection Scheme for 5G communications. *International Journal of Electrical and Computer Engineering (IJECE)*. 2018; 8(5): 2967–2978.
- [19] Rappaport TS, Gutierrez F, Ben-Dor E, Murdock JN, Qiao Y, Tamir JI. Broadband millimeter-wave propagation measurements and models using adaptive-beam antennas for outdoor urban cellular communications. *IEEE transactions on antennas and propagation*. 2013; 61(4): 1850-1859.
- [20] Maccartney GR, Rappaport TS. *73 GHz Millimeter Wave Propagation Measurements for Outdoor Urban Mobile And Backhaul Communications in New York City*. 2014 IEEE International Conference on Communications (ICC). Sydney. 2014: 4862–4867.
- [21] Zhao H, Mayzus R, Sun S, Samimi M, Schulz JK, Azar Y, Wang K, Wong GN, Gutierrez F, Rappaport TS. *28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York City*. 2013 IEEE International Conference on Communications (ICC). Budapest. 2013:5163-5167.
- [22] Hu F. Opportunities in 5G networks. A research and development perspective. United State : CRC press. 2016: 1-523.
- [23] Rappaport TS, Murdock JN, Gutierrez F. State of the art in 60-GHz integrated circuits and systems for wireless communications. *Proceedings of the IEEE*. 2011; 99(8): 1390-1436.
- [24] Bhushan N, Li J, Malladi D, et al. Network densification: the dominant theme for wireless evolution into 5G. *IEEE Communications Magazine*. 2014; 52(2): 82-89.
- [25] Attiah ML, Ismail M, Nordin R, Abdullah NF. *Dynamic Multi-state Ultra-wideband mm-wave Frequency Selection for 5G communication*. 2015 IEEE 12<sup>th</sup> Malaysia International Conference on Communications (MICC). Kuching. 2016: 219-224.