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Energy-efficient user association mechanism enabling fully hybrid spectrum sharing among multiple 5G cellular operators

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Abstract

Spectrum sharing (SS) is a promising solution to enhance spectrum utilization in future cellular systems. Reducing the energy consumption in cellular networks has recently earned tremendous attention from diverse stakeholders (i.e., vendors, mobile network operators (MNOs), and government) to decrease the CO2 emissions and thus introducing an environment-friendly wireless communication. Therefore, in this paper, joint energy-efficient user association (UA) mechanism and fully hybrid spectrum sharing (EE-FHSS) approach is proposed considering the quality of experience QoE (i.e., data rate) as the main constraint. In this approach, the spectrum available in the high and low frequencies (28 and 73 GHz) is sliced into three portions (licensed, semi-shared, and fully-shared) aims to serve the users (UEs) that belong to four operators in an integrated and hybrid manner. The performance of the proposed QoE-Based EE UA-FHSS is compared with the well-known maximum signal-to-interference-plus-noise ratio (max-SINR UA-FHSS). Numerical results show that remarkable enhancement in terms of EE for the four participating operators can be achieved while maintaining a high degree of QoE to the UEs.

***Keywords**: energy efficiency, green 5G communication, hybrid spectrum sharing (HSS)*

1. Introduction

The envisioned enormous growth in the diverse innovative technologies and services in future cellular communication era (i.e., Internet of Things (IoT), autonomous driving, augmented reality, and virtual reality) are resulting in increased demand for higher spectral and energy efficiency to meet such bandwidth and energy-hungry applications [1, 2]. Given the excellent opportunities of mmWave frequencies such as the huge amount of spectrum as well as the super interference-reduction merits [3], achieving success in relying on such technology became very possible [4]. Despite such a wide spectrum range, it is still not unlimited if other services that utilize the same bands are considered [5]. Nevertheless, due to the limited coverage range of mmWave communications [6], adding more minicell towers or relays throughout the hot spot area is essential to achieve better QoS. This may exacerbate the problem of energy consumption as more mmWave base stations (mBSs) are deployed. In particular, BSs are considered the main source of energy consumption in cellular networks, accounting for 57% of total energy requirements [7]. Spectrum sharing approach (SSA) can be a possible solution in the 5th generation (5G) mobile networks to overcome the above-mentioned issues [8]. Such an approach allows multiple users (UEs) to share the same resources in the power domain [9] which in turn supports massive connectivity using the same time-frequency resource with an acceptable mBSs density. Therefore, it is imperative to assess the system performance considering SSA from the energy consumption perspective as it considered as a fundamental design objective for the next generation cellular networks [10]. Through the literature, plenty of efforts have been conducted seeking for an environment-friendly wireless communication that involves a single-radio access technology (S-RATs). However, it is expected that 5G will support multi-RATs to provide ultra-reliable communication [11]. Consequently, many scholars are shifted from assessing the energy

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efficiency (EE) of the cellular systems that support S-RATs to those with multi-RATs capabilities, especially with the presence of resource sharing approach. For instance, joint spectrum and energy efficient mmWave transmission scheme was presented in [12] that combines the notion of non-orthogonal multiple access (NOMA) with beam space multiple-input multiple output (MIMO). Power control and allocation are targeted by many researches to improve EE by means of utilising different transmission power value in an adaptive way. The idea of jointly optimising cell-association and power-control was proposed in [13] taking the fast vehicle mobility and the traffic load conditions into consideration. In [14], a new adaptive spectrum sharing schemes account for the channel estimation errors to improve EE considering both half-duplex (HD) and full-duplex (FD) transmission. However, this scheme gave the priority to the primary users (PUs).

Most of the existing works on multi-independent 5G mmWave cellular operators have focused on coverage and rate probability optmisation [3, 5, 15–21]. There are limited works on energy-efficient UA that support spectrum sharing among multiple cellular operators, which is more complicated owing to the multi-carrier and multi-independent-RAT nature. Therefore, in this paper, energy efficient UA mechanism enabling FHSS approach underlying multi-independent 5G mmWave cellular operators is proposed while satisfying the QoE (i.e., rate provisioning) constraints to the UEs to gain more insights about the possibility of jointly maximising energy efficiency for all the participating operators taking into account maintaining an acceptable level of 5G constraints.

2. Research Method

In this section, we first elaborate on the network model, followed by a set of mathematical models related to the transmission model. Finally, some detailed description of the proposed EE-FHSS approach is presented.

2.1. Network Model

Two tiers of multi-independent 5G mmWave cellular operators given by $\mathcal{N}$. Four operators are considered in this work underlying spectrum sharing approach in which each operator $\mathcal{N}^{th}$ constituted of a set of mmWave base stations (mBSs) distinguished by $\mathcal{K}_{\mathcal{N}}^{th}$. Each $\mathcal{K}_{\mathcal{N}}^{th}$ operates optionally at both carrier frequencies (28 and 73 GHz) depends on the value of $\mathcal{C}_m \in \{0,1\}$ such that if $\mathcal{C}_m$=0 then the carrier is 28 GHz and if $\mathcal{C}_m$=1 then the carrier is 73 GHz. More precisely, each $\mathcal{K}_{\mathcal{N}}^{th}$ operates in a particular mode (licensed, semi-pooled, fully-pooled) based on the index m. Let $\mathcal{W}_{\mathcal{N},\mathcal{C}}$ stands for the allocated spectrum to each operator $\mathcal{N}^{th}$. Let $\mathcal{K}_{\mathcal{N}}$ be a set of mBSs belong to operator $\mathcal{N}^{th}$ and $\mathcal{K} = \mathcal{K}_1 \cup \mathcal{K}_1 \dots \cup \mathcal{K}_{th}$ refers to a set of all mmWave base stations in the proposed architecture. Motivated by 5G small cells can be easily attached to the street light poles, all mBSs are densely deployed following grid-based layout in a hot spot area $\mathbb{R}^2$. Let $\mathcal{U}$ denotes a set of outdoor user equipments (UEs) and $\mathcal{U} = \mathcal{U}_1 \cup \mathcal{U}_1 \dots \cup \mathcal{U}_{\mathcal{N}}$, where, $\mathcal{U}_{\mathcal{N}}$ represents a set of UEs that subscribes to an operator $\mathcal{N}^{th}$. $\mathcal{K}_{\mathcal{N}}$ can serve $\mathcal{U}^{(th,\mathcal{N})}$ which are subscribing to its own or to different operator via licensed, semi-shared or fully-shared spectrum access strategy and the quality of the link between the $\mathcal{U}^{(th,\mathcal{N})}$ and the tagged $\mathcal{K}_{\mathcal{N}}^{th}$. Furthermore, all UEs are equipped with multi-antenna systems.

2.2. Transmission Model

In this work, the log-normal shadowing path-loss model given by (1) is utilized to compute the received signal power at the receiving side (RX) with path-loss exponent γ and wavelength (3.4, 3.3 dB and 10.71, 4.106 mm) for both 28 GHz and 73 GHz carrier frequency respectively [22]:

$$PLd_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})} = PL_{fs}(d_o) + 10 \times \gamma \times log_{10}\left(\frac{d_{\mathcal{UK}}}{d_o}\right) + x_\sigma, \quad (1)$$

where $PLd_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}$, $d_{\mathcal{UK}}$, $PL_{fs}(d_o)$ stand for the path loss in dB for a typical UE $\mathcal{U}^{(th,\mathcal{N})}$ associated with mBS $\mathcal{K}_{\mathcal{N}}^{th}$ utilising carrier frequency $\mathcal{C}$ and owned by operator $\mathcal{N}^{th}$, the separation distance in meters, and the close-interference free space path loss in dB as identified in (2) respectively. Considering the close-in free space reference distance d_o is equal to 1 meter; x_σ denotes zero-mean Gaussian random variable with σ as a standard deviation in (dB).

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

Typically, one of the most important factors in the calculation of the average received signal power at the receiver side is the path loss attenuation. Therefore, we first apply (1) to calculate the path loss attenuation and then execute (3) as follows:

$$\mathrm{Pr}_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})} = \mathrm{P_t}{}^{(\mathcal{N},\mathcal{C})} + G_t{}^{(\mathcal{N},\mathcal{C})} + G_r{}^{(\mathcal{N},\mathcal{C})} - PL_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})} \quad (3)$$

where $\mathrm{P_t}^{(\mathcal{N},\mathcal{C})}$ and $\mathrm{Pr}_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}$ are the transmitted and received power of mBS $\mathcal{K}_{\mathcal{N}}^{th}$ respectively which are controlled by operator $\mathcal{N}^{th}$ and operated at mmWave carrier frequency $\mathcal{C}$; $G_r{}^{(\mathcal{N},\mathcal{C})}$ and $G_t{}^{(\mathcal{N},\mathcal{C})}$ are the directivity gains of the receiver and transmitter antennas in dBi, respectively.

To characterise the performance of each participating operator, we consider the $SINR$ as an indication to assess the outage probability as given in (4) [23]. We assume that any user $\mathcal{U}^{(th,\mathcal{N})}$ be in outage if the $SINR$ value is below than ($Thd \leq 0$).

$$\Gamma_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})} = \frac{\mathrm{Pr}_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}}{\sum_{\mathrm{n=1}}^{\mathrm{N}} \mathrm{I}_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})} + \eta^{(\mathcal{N},\mathcal{C})}} \quad (4)$$

desired signal received by the receiver $\mathcal{U}^{th,\mathcal{N}}$; $\eta^{(\mathcal{N},\mathcal{C})}$ stands for the additive white noise power of $\mathcal{N}^{th}$ with respect to carrier frequency $\mathcal{C}$.

$\Gamma_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}$ calculation opens the way for further user channel capacity calculation utilising Shannon capacity theory as expressed in (5) [24]:

$$\mathfrak{D}_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})} = \text{Ч}_{\mathcal{K}}^{(\mathcal{N},\mathcal{C})} \times \left(\frac{\mathcal{W}^{(\mathcal{N},\mathcal{C})}}{all\mathcal{U}_{\mathcal{K}}^{th}}\right) \times log_2\left(1 + \Gamma_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}\right), \quad (5)$$

where $\text{Ч}_{\mathcal{K}}^{(\mathcal{N},\mathcal{C})}$ stands for the minimum number of antennas in the transmitter/receiver side; $\mathcal{W}_{\mathcal{N},\mathcal{C}}$ stands for the predefined amount of spectrum bandwidth allocated to $\mathcal{N}^{th}$; $\mathfrak{D}_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$ stands for the channel capacity of $\mathcal{U}^{(th,\mathcal{N})}$; $all\mathcal{U}_{\mathcal{K}}^{th}$ stands for the number of UEs associated with the serving $\mathcal{K}_{\mathcal{N}}^{th}$.

2.3. Energy Efficiency (EE) Model

In the literature, the definition of EE varies according to the measured objects. In a communication system, the generic energy efficiency calculation is modeled as the total sum rate of the whole system divided by the total power consumption. However, as the objective of this work is to maximize the EE for each individual UE-mBS link while maintaining a certain level of QoE to the UEs, an efficient UA is involved to associate the user with the mBSs that provides the best trade-off between rate provisioning and power consumption. Therefore, the EE is defined in (6) as the number of achievable bits divided by the consumed energy (bits/Joule) for the associated UE-mBS link represented by ($\mathcal{UK}$) [25]:

$$EE_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})} = \frac{\mathfrak{D}_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}}{P_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}}, \quad (6)$$

where $P_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$ is the total power consumption that consumed by the mBS which is equal to $\left(\frac{\mathrm{P_t}^{(\mathcal{N},\mathcal{C})}}{\mu} + P_{Circuit}^{\mathcal{K}}\right)$; μ and $P_{Circuit}^{\mathcal{K}}$ (0.25 and 0.1 mW) stands for amplifier efficiency and the circuit power consumed by each mBS respectively.

2.4. QoE-Based EE UA-FHSS Model

In this subsection, the most important QoE-Based EE UA-FHSS considerations are meticulously addressed underlying four multi-independent 5G mmWave cellular operators that share a chunk of its own spectrum bandwidth amongst each other based on a set of predefined roles (i.e., FHSS). Each operator adopts the same roles to associate a typical UE belong to its own operator (based on licensed spectrum access strategy) or to another operator (based on semi-fully shared spectrum access strategy) with the tagged mBSs that provides the best $\mathfrak{D}_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})} - EE_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$ trade-off to enhance the energy efficiency while retain a certain QoE to the UEs. More precisely, each operator $\mathcal{N}^{th}$ grants a licensed access to 250 MHz at 28 GHz carrier frequency (when $\mathcal{C}_m$ = 0) to $\mathcal{U}^{(ths,\mathcal{N})}$ which are subscribing to its own operator in order to evade inter-operator interference. Meanwhile, in the high carrier frequency 73 GHz, the spectrum (when $\mathcal{C}_m$ = 1) is divided into two portions, each with 500 MHz. The first portion (500 MHz) is shared among all operators. The second one (500 MHz) is sliced into two chunks each is assigned as semi-shared to only two operators. The first chunk (250 GHz) is granted to OP1 and OP4, and the second to OP2 and OP3. Based on that, there are three options for the UE (i.e., Raihana) to be associated with a particular $\mathcal{K}_{th,\mathcal{N}}$ as illustrated in Figure 1. Such association is performed based on the proposed QoE-Based EE UA-FHSS which makes a decision to associate (Raihana) with mBS1-OP2 as it offers the best $\mathfrak{D}_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})} - EE_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$ trade-off. The baseline (max-SINR UA-FHSS) is similar to the proposed QoE-Based EE UA-FHSS. Unlike, the UE (i.e., Raihana) is associated with mBS that provides the highest SINR. Based on the above-mentioned FHSS roles, we adopt both max-SINR UA-FHSS and QoE-Based EE UA-FHSS schemes as illustrated in Algorithm 1 to associate the UEs with $\mathcal{K}_{\mathcal{N}}^{th}$ that offers minimum energy consumption compared with the baseline max-SINR UA-FHSS which associates the UEs with $\mathcal{K}_{\mathcal{N}}^{th}$ that offers max-SINR.

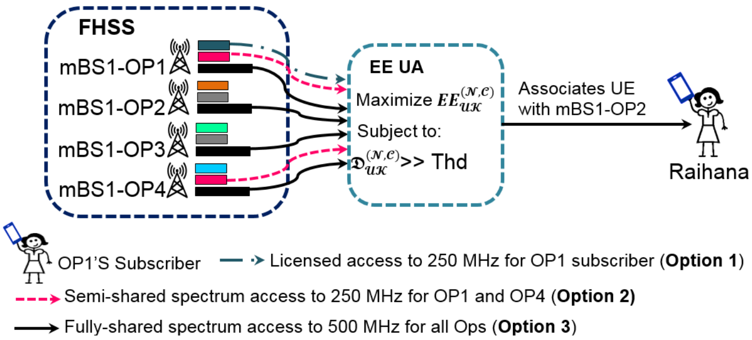

Figure 1. An illustration of EE UA FHSS scheme

Algorithm 1 Pseudocode of the implementation based on max-SINR and max-EE mUA-FHSS schemes

Input: Set the initial parameters of $\forall\, \mathcal{N}^{th} \in \mathcal{N}$, $\forall \mathcal{K}_{\mathcal{N}}^{th} \in \mathcal{K}$, $\forall \mathcal{U}^{(th,\mathcal{N})} \in \mathcal{U}$, $\forall\, \mathcal{W}_{\mathcal{N},\mathcal{C}}$, $\mathrm{P_t}^{\mathcal{M},S_\mathrm{K}}$, $\eta^{(\mathcal{N},\mathcal{C})}$, $G_t^{(\mathcal{N},\mathcal{C})}$, $G_r^{\mathcal{M},S_\mathrm{K}}$.

1 Deployment of $\forall \mathcal{K}_{\mathcal{N}}^{th}$, $\forall \mathcal{U}^{th,\mathcal{N}}$ all over the predetermined area (1.2 Km x 1.2 Km);

2 for $\forall \mathcal{U}^{(th,\mathcal{N})} \in \mathcal{U}$ & $\forall\, \mathcal{N}^{th} \in \mathcal{N}$ do

3 Calculate $d_{\mathcal{UK}}$ of $\forall \mathcal{U}^{th,\mathcal{N}}$ in terms of $\forall \mathcal{K}_{\mathcal{N}}^{th}$ that belong to the same or to the shared operator;

4 Calculate $PL_{fs}(d_o)$, $PLd_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}$, and $\mathrm{Pr}_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}$ of $\forall \mathcal{U}^{th,\mathcal{N}}$ by means (1), (2), a (3);

5 Calculate $\Gamma_{\mathcal{UK}}{}^{(\mathcal{N},\mathcal{C})}$ of $\forall \mathcal{U}^{(th,\mathcal{N})}$ in terms of $\forall \mathcal{K}_{\mathcal{N}}^{th}$ that belong to the same or the shared operator (4);

	max-SINR mUA-FHSS scheme	max-EE mUA-FHSS scheme
6	Associates $\forall \mathcal{U}^{(th,\mathcal{N})}$ to the serving $\mathcal{K}_{\mathcal{N}}^{th}$	Compute $\mathfrak{D}_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$ of $\forall \mathcal{U}^{(th,\mathcal{N})}$ according to (5);

that offers the highest $\Gamma_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$;
Calculate $\mathfrak{D}_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$ of $\forall\mathcal{U}^{(th,\mathcal{N})}$ according to (5);
end for

Calculate $EE_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$ of $\forall\mathcal{U}^{(th,\mathcal{N})}$ according to (6);
Associates $\forall\mathcal{U}^{(th,\mathcal{N})}$ to the tagged $\mathcal{K}_{\mathcal{N}}^{th}$ that offers the highest $EE_{\mathcal{UK}}^{(\mathcal{N},\mathcal{C})}$;
end for

Calculate the average rate $(Avg\mathfrak{D}\mathcal{N})$, where $\mathcal{N}$= {1,2,3… N};
Calculate the average EE $(AvgEE\mathcal{N})$, where $\mathcal{N}$= {1,2,3… N};
Output: average rate, average of EE, and CDFs of EE;

3. Results and Analysis

In this section, the performance of the proposed QoE-Based EE UA-FHSS is numerically evaluated considering both dissimilar spectrum allocation and hybrid mBSs deployment. Two main performance measures (average rate and energy efficiency) are adopted in the evaluation process to compare the proposed QoE-Based EE UA-FHSS with the baseline well-known max-SINR UA-FHSS. The related configurations and simulation parameter settings are listed in Table 1.

3.1. Average Rate Assessment

Some numerical results are described in this subsection which brings a confirmation that QoE-Based EE UA-FHSS achieves a good QoE to the UEs in terms of average rate via optimally choosing of the best EE and rate provisioning trade-off. The average rate of the UEs that are served by the four mmWave cellular operators based on the proposed QoE-Based EE UA-FHSS and the baseline max-SINR UA-FHSS is depicted on Figure 2. It is shown that a certain level of QoE (i.e., the average rate more than one gigabit per second) was achieved to satisfy the needs of the future 5G applications, while gaining more enhancement in the overall EE as will be discussed in the next subsection. Figure 2 also shows the superior performance of the proposed QoE-Based EE UA-FHSS over the baseline mechanism in terms of achieving higher data rate (more than two folds).

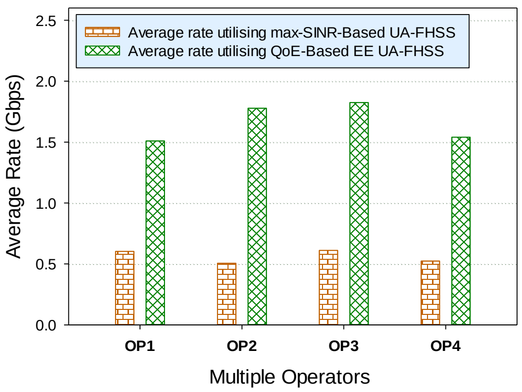

Figure 2. Average rate of the four participating cellular operators using QoE-Based EE and max-SINR-Based UA FHSS schemes

Table 1. Simulation Parameter Settings

Parameters	Description/value
MmWave Base Station Layout	Grid-based Cell Deployment
MmWave Base Station Density	16
Number of Operator	4
UE Density	160 Users
Area of Simulation	1.2 Km2
Inter-Site-Distance (ISD)	300 m
mBS Carrier Frequency	28GHz and 73GHz
mBS Transmit Power	30 dBm
Noise Figure (US)	6 dB
Variant of White Gaussian Noise	-174 dBm/Hz
mBS Bandwidth	1GHz for 28GHz and 73GHz

3.2. Energy Efficiency Distribution

In this subsection, the focus of attention is to analyse the system performance in terms of EE for all participating operators. Figures 3 (a-d) show the energy efficiency distribution of OP1, OP2, OP3, and OP4 respectively. Notably, the proposed QoE-Based EE UA-FHSS outperforms the most conventional max-SINR UA-FHSS mechanism in terms of EE distribution where on average more than (90%) of the UEs that belong to the four operators experience more than (100 Mb/Joule) compared to (45%) with the adoption of the baseline UA (max-SINR UA-FHSS). Furthermore, as depicted in Figure 4, the average of EE of the four multi-independent 5G mmWave cellular operators utilizing QoE-Based EE UA-FHSS significantly outweighs the baseline max-SINR UA-FHSS. More precisely, it was realized that the average of EE of each participating operator is more than (350 Mb/Joule), achieving an improvement more than two-fold over the baseline UA. This resulted from the enhancement of the experienced rate.

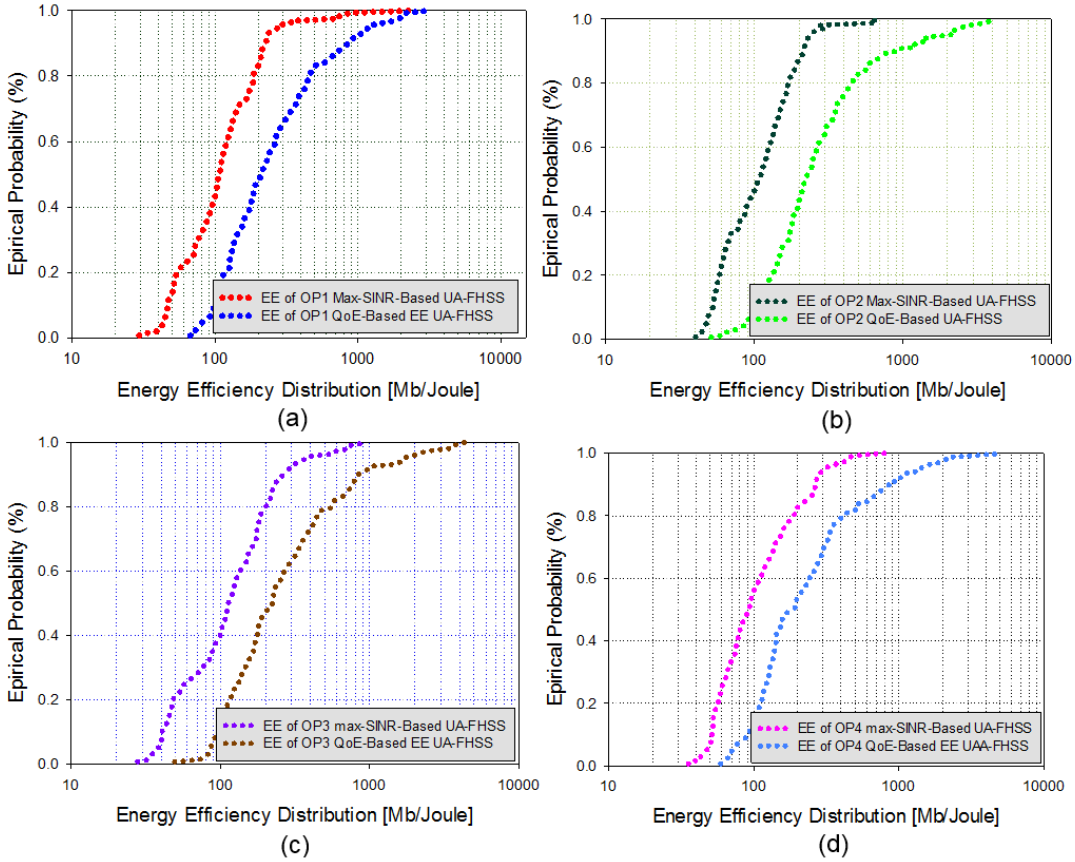

Figure 3. A comparison of the CDFs of EE of the four mmWave cellular operators utilising both our proposed QoE-Based EE-FHSS and the baseline max-SINR UA-FHSS (a) OP1, (B) OP2, (c) OP3, (d) OP4

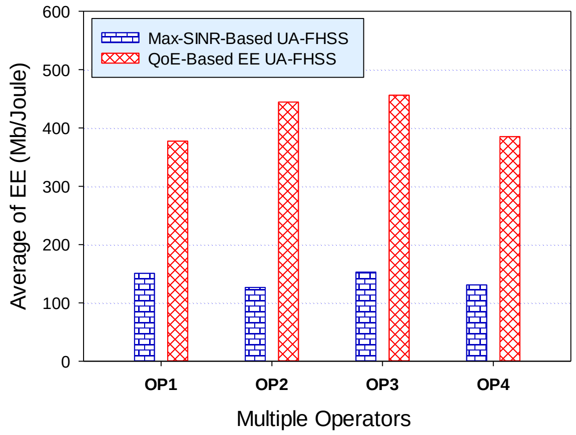

Figure 4. Average of energy efficiency of the four operators utilizing QoE-Based EE UA-FHSS and max-SINR UA FHSS

4. Conclusion

In this article, green and QoE-Based UA involving spectrum sharing approach is presented considering multi-independent 5G mmWave cellular operators. Three spectrum access strategies (licensed, semi-shared and fully-shared) are integrated in a hybrid manner to provide an order of magnitude enhancement in both spectrum utilisation and individual UE-mBS energy consumption. The numerical results show that such hybrid integration with its own nature (i.e., diversity) can effectively enhance the data rate by means of reducing the mutual interference issues amongst the participating operators. Furthermore, the utilization of the proposed QoE-Based EE UA-FHSS attains considerable improvement in EE compared with the max-SINR-Based UA-FHSS. The EE of the four mmWave cellular operators with the adoption of QoE-Based EE UA-FHSS are improved with more than two folds over the baseline max-SINR-Based UA-FHSS. Moreover, it enables a rapid creation of new wireless applications or merging more than one operator (i.e. MergedCo) in a cost-effective manner due to the reduction of operation expenditure (OpEx). In future work, we will expand this analysis by means of involving more complex UA mechanism such as multi criteria decision-making approach considering diverse services and applications requirements.

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