On Evaluating Spectrum Allocation Techniques in Millimeter-Wave Systems Using Indoor Smalls for 5G/6G

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***Abstract*— In this paper, we present three spectrum allocation techniques, namely Static and Equal Spectrum Allocation (SESA), Flexible and Unequal Spectrum Allocation (FUSA), and Countrywide Full Spectrum Allocation (CFSA), and evaluate their performances for the 28 GHz millimeter-wave spectrum using in-building small cells. We discuss each technique broadly by identifying major concerns, presenting possible solutions, as well as evaluating performances relative to each other in terms of Spectral Efficiency (SE), Energy Efficiency (EE), and Cost Efficiency (CE). It is found that FUSA improves SE by 22.8%, EE by 18.56%, and CE by 18.56%, whereas CFSA improves SE by 164.27%, EE by 74.77%, and CE by 59.64% in comparison with that of SESA. As CFSA outperforms SESA and FUSA, CFSA can be considered as a potential spectrum allocation technique for the existing and next-generation mobile networks to allow a large spectrum availability, as well as efficient spectrum utilization, for an operator to serve high indoor data rates and capacity demands.**

Keywords-28 GHz; spectrum allocation; millimeter-wave; small cell; spectrum utilization; technique.

I. INTRODUCTION

Spectrum allocation techniques have a significant impact on the efficient utilization of the radio spectrum in mobile communication systems [1]. Traditionally, each Mobile Network Operator (MNO) in a country is allocated statically and exclusively to an equal amount of the licensed spectrum (termed as Static and Equal Spectrum Allocation (SESA)) for a long term, irrespective of the demand of its users. Since the demand for user traffic of different MNOs in a country varies with time and locations, the requirements of the spectra of MNOs also vary accordingly. Due to this phenomenon, a great portion of the allocated spectrum to an MNO may be either unused or underutilized [2]-[3], while another MNO at the same time and location may suffer from an insufficient amount of spectrum. This, in turn, results in low spectrum utilization and Quality-of-Service (QoS), which raises concerns over how to allocate the spectrum among MNOs such that the required user demand can be served while ensuring an efficient countrywide spectrum utilization.

One way to address this concern is to allocate spectrum to each MNO based on the actual requirement to serve its user traffic [4]. In this regard, a simple, yet effective, measure to define the actual requirement for an MNO is to allocate spectrum flexibly in accordance with its number of subscribers. Since the number of subscribers of an MNO is usually different from that of other MNOs, such a flexible and on-demand spectrum allocation technique allocates an unequal amount of spectrum to MNOs (termed as Flexible and Unequal Spectrum Allocation (FUSA)), unlike SESA. Also, to address frequent variations in the statistics of subscribers of MNOs, in FUSA, the allocation of spectrum to each MNO needs to be updated in the short term, unlike SESA.

Another key technique to address an efficient spectrum utilization and the required QoS is to allow access to the countrywide full spectrum to each MNO subject to managing Co-Channel Interference (CCI) from one MNO to another (termed as Countrywide Full Spectrum Allocation (CFSA)). In this regard, since different MNOs have a different number of subscribers, an MNO can pay the spectrum licensing fee for a short term based on its number of subscribers with respect to the total number of subscribers countrywide to ensure fairness. Note that CFSA takes advantage of allocating a large amount of spectrum to each MNO to address the required QoS, as well as the dynamic allocation of the spectrum to each MNO corresponding to serving its user demand to address an efficient countrywide spectrum utilization. Figure 1 shows an illustration of allocating the countrywide spectrum to MNOs using SUSA, FUSA, and CFSA techniques.

Since existing and next-generation mobile networks will be spectrum hungry to serve a high data rate and a large volume of traffic, particularly in urban multistory buildings, ensuring high spectrum bandwidth is one of the major concerns to MNOs. To address the high bandwidth availability for an MNO indoors, the Millimeter-Wave (mmWave) spectrum is considered as an effective solution. In this regard, the 28 GHz band has been considered as a potential mmWave band due to its favorable indoor characteristics to address a high data rate and capacity demand within a short distance. Hence, in this paper, we intend to evaluate the SESA, FUSA, and CFSA techniques indoors for 28 GHz spectrum in terms of Spectral Efficiency (SE), Energy Efficiency (EE), and Cost Efficiency (CE).

II. MATHEMATICAL ANALYSIS

Let O denote the maximum number of MNOs in a country such that $o \in \boldsymbol{O} = \{1, 2, ..., O\}$. Let M_{C} and N_{C} denote the countrywide 28 GHz mmWave spectrum and the total number of users of all MNOs in a country,

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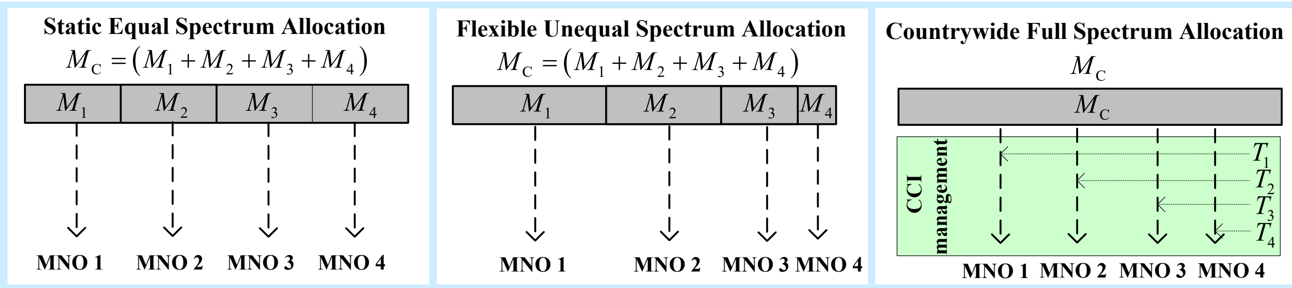

Figure 1. An illustration of SESA, FUSA, and CFSA techniques at any term t_{r}.

respectively. M_{C} is expressed in terms of the number of Resource Blocks (RBs) where an RB is equal to 180 kHz such that $\sum_{o=1}^{O} M_{o,t_{\mathrm{r}}} \le M_{\mathrm{C}}$, as well as $\sum_{o}^{O} N_{o,t_{\mathrm{r}}} \le N_{\mathrm{C}}$, at any license renewed term t_{r}. Now, based on the aforementioned criterion for each technique, the amount of allocated spectrum to an MNO o in SESA at any term t_{r} can be given by $M_{o,t_{\mathrm{r}}} = M : o \in \boldsymbol{O}$, where M is the same for all MNOs. Likewise, the amount of allocated spectrum to an MNO o in FUSA at term t_{r} can be given by $M_{o,t_{\mathrm{r}}} = \left(N_{o,t_{\mathrm{r}}} \times M_{\mathrm{C}}\right) / N_{\mathrm{C}} : o \in \boldsymbol{O}$, as shown in Figure 1.

However, in CFSA, the amount of spectrum allowed to be accessed by each MNO at term t_{r} is given by $M_{o,t_{\mathrm{r}}} = M_{\mathrm{C}} : t \in \boldsymbol{T}^{\mathrm{nA}}_{o,t_{\mathrm{r}}} \wedge o \in \boldsymbol{O}$ where $\boldsymbol{T}^{\mathrm{nA}}_{o,t_{\mathrm{r}}}$ denotes a set of Transmission Time Intervals (TTIs) t during which an MNO o can get access to M_{C} in an observation period $\boldsymbol{T}$ with the maximum time of Q (in time step each lasting 1 ms) such that $t \in \boldsymbol{T}$. Since each MNO is allocated to the same spectrum, CCI can occur in CFSA. We consider the time-domain CCI management as an example. Hence, to avoid CCI in time-domain, we consider time orthogonality in allocating the full spectrum to small cell User Equipments (UEs) of all MNOs such that in any TTI t Small cell UEs (SUs) of only one MNO in a building can be scheduled using techniques, such as the Almost Blank Subframe (ABS) based Enhanced Intercell Interference Coordination (eICIC) [5]-[6].

Assume that the number of TTIs per ABS Pattern Period (APP) t_{APP} allocated to any UE of an MNO o is the number of non-ABSs allocated to the corresponding MNO o over t_{APP} in any building, which is defined as follows. The number of non-ABSs per APP allocated to any UE of an MNO o in a building is defined in accordance with the ratio of the number of subscribers $N_{o,t_{\mathrm{r}}}$ of the MNO o at any renewed term t_{r} to the sum of the number of subscribers of MNOs $\boldsymbol{O}\backslash o$ (plus $N_{o,t_{\mathrm{r}}}$ of MNO o) so that at least an SU corresponding to the MNO $\boldsymbol{O}\backslash o$ is present within the same building in any TTI t of the previous APP $\left(t_{\mathrm{APP}} - 1\right)$.

Let $\boldsymbol{T}^{\mathrm{A}}_{o,t_{\mathrm{r}}}$ and $\boldsymbol{T}^{\mathrm{nA}}_{o,t_{\mathrm{r}}}$ denote, respectively, a set of all ABSs and a set of all non-ABSs at term t_{r} for an MNO $o \in \boldsymbol{O}$ at all APPs in $\boldsymbol{T}$, such that $T^{\mathrm{A}}_{o,t_{\mathrm{r}}} \in \boldsymbol{T}^{\mathrm{A}}_{o,t_{\mathrm{r}}}$, $T^{\mathrm{nA}}_{o,t_{\mathrm{r}}} \in \boldsymbol{T}^{\mathrm{nA}}_{o,t_{\mathrm{r}}}$, and $\boldsymbol{T} = \boldsymbol{T}^{\mathrm{A}}_{o,t_{\mathrm{r}}} + \boldsymbol{T}^{\mathrm{nA}}_{o,t_{\mathrm{r}}}$. Hence, the number of non-ABSs (i.e., operating time) $T^{\mathrm{nA}}_{o,t_{\mathrm{r}}}$ of small cells of MNO o at term t_{r} to use the full countrywide spectrum using CFSA for O=4 at any t_{APP} [7] is given by

$$T^{\mathrm{nA}}_{o,t_{\mathrm{r}}} = \left\lceil \left(\left(N_{o,t_{\mathrm{r}}} \middle/ \sum_{o=1}^{O} \left(1_{\nu_o}\left(N_{o,t_{\mathrm{r}}}\right) N_{o,t_{\mathrm{r}}} \right) \right) \times T_{\mathrm{APP}} \right) \right\rceil \tag{1}$$

where $\nu_o \in \left\{ N_{1,t_{\mathrm{r}}}, N_{2,t_{\mathrm{r}}} N_{3,t_{\mathrm{r}}}, N_{4,t_{\mathrm{r}}} \right\}$. $1(\cdot)$ is defined such that $1(\cdot) = 1$ if $N_{o,t_{\mathrm{r}}}$ exists in the set ν_o; otherwise, $1(\cdot) = 0$. T_{APP} denotes the duration of an APP in TTIs.

III. PROBLEM FORMULATION

Let S_{F} denote the maximum number of small cells in a building such that $s \in \{1,2,...,S_{\mathrm{F}}\}$. Let S_{M} denote the number of macrocells, and let S_{P} denote the number of picocells per macrocell of each MNO. Let P_{M}, P_{P}, and P_{S} denote, respectively, the transmission power of a macrocell, a picocell, and a small cell of an MNO o. Using Shannon's capacity formula, a link throughput at RB=i in TTI=t for an MNO o at term t_{r} in bps per Hz is given by [8]

$$\sigma^{t_{\mathrm{r}}}_{t,i,o}\left(\rho^{t_{\mathrm{r}}}_{t,i,o}\right) = \left\{ \begin{array}{ll} 0, & \rho^{t_{\mathrm{r}}}_{t,i,o} < -10\,\mathrm{dB} \\ \beta \log_2\left(1 + 10^{\left(\rho^{t_{\mathrm{r}}}_{t,i,o}(\mathrm{dB})/10\right)}\right), & -10\,\mathrm{dB} \le \rho^{t_{\mathrm{r}}}_{t,i,o} \le 22\,\mathrm{dB} \\ 4.4, & \rho^{t_{\mathrm{r}}}_{t,i,o} > 22\,\mathrm{dB} \end{array} \right\} \tag{2}$$

where β denotes the implementation loss factor.

Let $M_{\mathrm{MBS},o}$ denote the spectrum in RBs of a macrocell for an MNO o. Then, the total capacity of all macrocell UEs for an MNO o at t_{r} can be expressed as

$$\sigma^{t_{\mathrm{r}}}_{\mathrm{MBS},o} = \sum_{t=1}^{Q} \sum_{i=1}^{M_{\mathrm{MBS},o}} \sigma^{t_{\mathrm{r}}}_{t,i,o}\left(\rho^{t_{\mathrm{r}}}_{t,i,o}\right) \tag{3}$$

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where σ and ρ are responses over $M_{\mathrm{MBS},o}$ RBs of all macro UEs in $t \in \boldsymbol{T}$ for an MNO o at t_{r}.

If all Small cell Base Stations (SBSs) in a multistory building serve simultaneously in t, the aggregate capacity served by all SBSs in a building of an MNO o at term t_{r} is given by

$$\sigma_{S_{\mathrm{F}},o}^{t_{\mathrm{r}}} = \sum_{s=1}^{S_{\mathrm{F}}} \sum_{t} \sum_{i=1}^{M_{o,t_{\mathrm{r}}}} \sigma_{t,i,o}^{t_{\mathrm{r}}} \left(\rho_{t,i,o}^{t_{\mathrm{r}}}\right) \tag{4}$$

Let us define Cost Efficiency (CE) as the cost required per unit achievable average capacity (i.e., per bps). Let ε_{C} denote the cost of M_{C} such that an MNO o pays $\varepsilon_{o,t_{\mathrm{r}}}$ for its licensed spectrum $M_{o,t_{\mathrm{r}}}$ at t_{r}. The system-level average aggregate capacity, SE, EE, and CE for all MNOs O countrywide at t_{r} for all techniques are given, respectively, by

$$\sigma_{\mathrm{cap},O}^{\mathrm{sys},t_{\mathrm{r}}} = \sum_{o=1}^{O} \left(\sigma_{\mathrm{MBS},o}^{t_{\mathrm{r}}} + \sigma_{S_{\mathrm{F}},o}^{t_{\mathrm{r}}}\right) \tag{5}$$

Since $\sigma_{S_{\mathrm{F}},o}^{t_{\mathrm{r}}} >> \sigma_{\mathrm{MBS},o}^{t_{\mathrm{r}}}$, $\sigma_{\mathrm{cap},O}^{\mathrm{sys},t_{\mathrm{r}}} \cong \sum_{o=1}^{O} \sigma_{S_{\mathrm{F}},o}^{t_{\mathrm{r}}}$

$$\sigma_{\mathrm{SE},O}^{\mathrm{sys},t_{\mathrm{r}}} = \sigma_{\mathrm{cap},O}^{\mathrm{sys},t_{\mathrm{r}}} \Big/ \left(\sum_{o=1}^{O} \left(M_{\mathrm{MBS},o} + M_{o,t_{\mathrm{r}}}\right) \times Q\right) \tag{6}$$

$$\sigma_{\mathrm{EE},O}^{\mathrm{sys},t_{\mathrm{r}}} = \left(O\left(S_{\mathrm{F}} P_{\mathrm{S}} + S_{\mathrm{P}} P_{\mathrm{P}} + S_{\mathrm{M}} P_{\mathrm{M}}\right)\right) \Big/ \left(\sigma_{\mathrm{cap},O}^{\mathrm{sys},t_{\mathrm{r}}} / Q\right) \tag{7}$$

$$\varsigma_{\mathrm{CE},O}^{\mathrm{sys},t_{\mathrm{r}}} = \varepsilon_{\mathrm{C}} \big/ \sigma_{\mathrm{cap},O}^{\mathrm{sys},t_{\mathrm{r}}} \tag{8}$$

where $t \in \left\{ \begin{array}{ll} \boldsymbol{T}, & \text{for SESA} \\ \boldsymbol{T}, & \text{for FUSA} \\ \boldsymbol{T}_{o,t_{\mathrm{r}}}^{\mathbf{nA}}, & \text{for CFSA} \end{array} \right\}$ and

$$M_{o,t_{\mathrm{r}}} = \left\{ \begin{array}{ll} M, & \text{for SESA} \\ \left(N_{o,t_{\mathrm{r}}} M_{\mathrm{C}}\right) \big/ N_{\mathrm{C}}, & \text{for FUSA} \\ M_{\mathrm{C}}, & \text{for CFSA} \end{array} \right\}.$$

IV. PERFORMANCE EVALUATION

A. Performance Result

Table I shows selected assumptions and parameters used for the performance evaluation. Detailed assumptions and parameters can be found in [7]. Figure 2 shows the outperformance of FUSA and CFSA techniques with respect to the traditional SESA in terms of countrywide SE, EE, and CE. It can be seen that FUSA improves SE by 22.8%, EE by 18.56%, and CE by 18.56%, whereas CFSA improves SE by 164.27%, EE by 74.77%, and CE by 59.64% in comparison with that of SESA. Hence, due to allowing dynamic access to the countrywide full mmWave spectrum to each MNO to utilize the full spectrum efficiently, CFSA provides the best SE, EE, and CE performances of all techniques.

TABLE I. DEFAULT PARAMETERS AND ASSUMPTIONS

Parameters and assumptions	Value
Countrywide 28 GHz spectrum, MNOs, and subscribers	200 MHz; 4; N_{C}
Number of subscribers for MNOs 1, 2, 3, and 4	20%, 30%, 20% and 10% of N_{C}
E-UTRA simulation case[1]	3GPP case 3
Small cell model[2]	A building with square-grid apartments
Number of small cells	48
Observation time	8 ms

Taken [1]from [9] and [2]from [10].

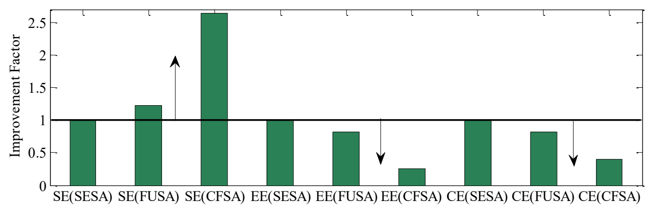

Figure 2. Performances of FUSA and CFSA with respect to SESA.

B. Issues with CFSA Implementation

Though CFSA provides the best performances of all techniques, a number of issues regarding, for example, its implementation, need to be addressed, as indicated below.

1) CCI management system: A key issue with CFSA is the co-channel interference generated when UEs of more than one MNO intend to access the countrywide spectrum. Though CCI can be managed, it requires additional management mechanisms either in time, frequency, or power domain, which, in turn, cause additional complexity and cost. For example, depending on the spectrum sensing techniques, such as either proactive or reactive, as well as management approaches, e.g. either centralized or distributed, the control signaling overhead may vary. More specifically, in the centralized management, though the global optimization of network performance can be obtained, it suffers from a large control signaling overhead in the network. In contrast, in the distributed management, the control signaling overhead is reduced by allowing the local network performance optimization.

2) Countrywide spectrum manager: Since all MNOs access the same countrywide spectrum, a common spectrum manager may be necessary to communicate and coordinate a timely and fair allocation of the spectrum to each MNO. In this regard, the deployment of the spectrum manager, the degree of information to be shared by each MNO with the spectrum manager, and tight coordination to allocate the spectrum among MNOs timely and fairly are a few challenges that need to be addressed for the spectrum manager.

3) Spectrum licensing fees: Distributing the licensing fee among MNOs in a country and the duration of the spectrum license renewed term t_{r} need a common mutual understanding among MNOs in a country, which sometimes may not be possible due to the competitive nature of MNOs in the market. In such a case, the central administration by the spectrum regulatory bodies may be required to sort out the issues among MNOs countrywide [11].

V. Conclusion

In this paper, we have presented three spectrum allocation techniques, namely SESA, FUSA, and CFSA, and shown that CFSA outperforms SESA and FUSA techniques in SE, EE, and CE such that CFSA can be considered as a potential spectrum allocation technique for Fifth Generation (5G)/Sixth Generation (6G) mobile networks.

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