Dynamic Spectrum Sharing in Multi-Operator Millimeter-Wave Indoor Systems

Rony Kumer Saha
Radio and Spectrum Laboratory
KDDI Research, Inc.
2-1-15 Ohara, Fujimino-shi, Saitama, Japan
email: ro-saha@kddi-research.jp

***Abstract*—A Dynamic Spectrum Sharing (DSS) technique is presented, which allows dynamic access to the countrywide full 28 GHz Millimeter-Wave (mmWave) spectrum to an arbitrary number of Mobile Network Operators (MNOs) to serve their respective in-building Small Cells (SCs). Co-Channel Interference (CCI) is managed by controlling the transmission power of in-building SCs of each MNO. Using the Equal Likelihood Criterion and the properties of left-justified Pascal's triangle, we derive the system-level average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) performance metrics. We carry out numerical analyses and simulation results for a country with four MNOs. It is shown that the proposed DSS can improve SE by about 2.64 times and EE by about 74.28% over that of the Static Equal Spectrum Allocation (SESA). Moreover, we show that the proposed DSS requires the reuse of the countrywide mmWave spectrum to 71.87% fewer buildings of SCs than that required by the SESA to satisfy the expected SE and EE requirements for the Sixth-Generation (6G) mobile systems.**

Keywords—28 GHz*; *spectrum sharing; multi-operator; indoor; millimeter-wave; technique; small cell.

I. INTRODUCTION

Addressing high capacity and data rate demands with limited spectrum bandwidth allocated to a Mobile Network Operator (MNO) has become a major issue for the Fifth-Generation (5G) and beyond mobile systems. Since the achievable capacity is directly proportional to the spectrum bandwidth of an MNO, an effective approach to address high capacity and data rate is to allow each MNO to access the full spectrum in a country. However, allowing access to the Countrywide Full-Spectrum (CFS) to each MNO causes Co-Channel Interference (CCI), which can be managed in the Power-Domain (PD).

The concept of countrywide full spectrum allocation and sharing is not so obvious in the existing literature. Saha [1] proposed a hybrid interweave-underlay CFS allocation in the 28 GHz band by managing CCI in the PD. CFS allocation in the 28 GHz has been investigated later in Saha [2] by managing CCI in the time-and frequency-domain. However, in both studies, the analyses were limited to a specific number of MNOs in a country. In this paper, we relax the assumptions in Saha [1] and Saha [2] and present a Dynamic Spectrum Sharing (DSS) technique for an arbitrary number of MNOs in a country. Unlike the traditional DSS techniques in 5G New Radio (NR) where each MNO (allocated to a portion of the countrywide full spectra) shares its spectrum dynamically with other MNOs countrywide, the proposed DSS technique allows access to the countrywide full 28 GHz spectrum to each MNO dynamically to serve its in-building Small Cells (SCs) by controlling the transmission power of SCs within each building using the Equal Likelihood Criterion and the properties of left-justified Pascal's triangle.

We organize the paper as follows. In Section II, the system architecture and the proposed DSS technique are described. Relevant mathematical analysis of DSS is carried out in Section III and performance evaluation and comparison are performed in Section IV. We conclude the paper in Section V.

II. SYSTEM ARCHITECTURE AND PROPOSED DSS TECHNIQUE

A. System Architecture

The system architecture consists of an arbitrary number of O MNOs in a country, which is shown in Figure 1(a) for O=4. Considering a similar architectural feature for each MNO, only one MNO (e.g., MNO 1) is shown in detail in Figure 1(c). An SC of each MNO is deployed in each apartment of a building. All Macrocells (MCs) and Picocells (PCs) operate at the 2 GHz outdoors, while SCs operate at the 28 GHz indoors. Let P_{m} and P_{r} denote the maximum and the reduced transmission powers of an SC of MNO o. Since all MNOs operate at the CFS, with an increase in the number of interferers, i.e., SC User Equipments (SUEs) of MNOs $\boldsymbol{O}\backslash o$, the aggregate interference from one SC to another increases. This causes the transmission power P_{r} of each SC of all MNOs to be adjusted such that the aggregate interference power does not exceed the interference threshold (i.e., the maximum value of CCI power) I_{m} . Let $\alpha_1, \alpha_2, \ldots \alpha_{(|\boldsymbol{O}|-1)}$ denote scaling factors and $\alpha_1 > \alpha_2 > \cdots > \alpha_{(|\boldsymbol{O}|-1)}$ implying the percentages of P_{m} to adjust P_{r} such that $\sum_{x=1}^{(|\boldsymbol{O}|-1)}(\alpha_x \times P_{\mathrm{m}}) \leq I_{\mathrm{m}}$. Figure 1(b) shows the transmission power levels of an SC to manage CCI for O=4. The existence of any interferer SUEs (iSUEs) of MNOs $\boldsymbol{O}\backslash o$ in an apartment can be detected by the SC of MNO o itself using any conventional spectrum sensing techniques to update the CCI and spectrum usage status real-time basis in every Transmission Time Interval (TTI) level by coordinating one MNO with another directly in a distributed manner [3].

B. Proposed DSS Technique

The proposed Dynamic Spectrum Sharing (DSS) technique is stated as follows. An MNO o can be allocated to the CFS dynamically to operate its in-building SCs, subjected to managing CCI with SCs of other MNOs $\boldsymbol{O}\backslash o$ over a certain license renewal term t_{r}. CCI is considered managing in the PD

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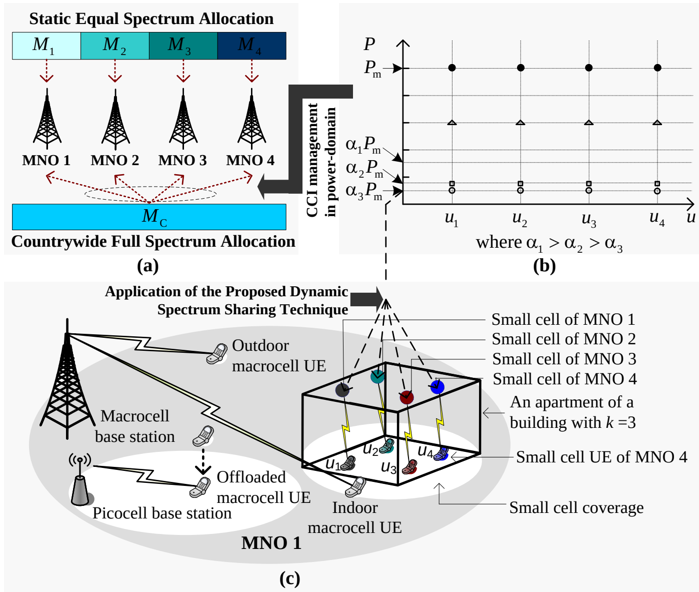

Figure 1. (a) Static Equal Spectrum Allocation (SESA) and CFS allocation. (b) Transmission power levels of an SC to manage CCI. (c) System architecture with 4 MNOs in a country.

by controlling the transmission power of each SC using the following principle. An SC of MNO o operates at the maximum transmission power if no SC User Equipment (UE) of MNOs $\boldsymbol{O}\backslash o$ is present, while at reduced power if an SUE of MNO $\boldsymbol{O}\backslash o$ is present, within the corresponding SC coverage of MNO o in a building. The reduced power is subjected to satisfying the maximum allowable CCI at the SC of MNO o.

III. Mathematical Analysis of DSS

Let O be the maximum number of MNOs in a country such that $o \in \boldsymbol{O} = \{1,2,...,O\}$. Let the amount of Millimeter-Wave (mmWave) spectrum allocated to an MNO o and a country, respectively, be M_o and M_C, defined in terms of the number of Resource Blocks (RBs) where an RB is equal to 180 kHz. Consider that each SC can serve one SUE at a time, and each combination of the coexistence of SUEs of MNOs $\boldsymbol{O}\backslash o$ (one UE from each MNO) with a UE of MNO o in an apartment is equally likely over any observation time $|\boldsymbol{T}| = Q$ and hence occurs with a probability of $\left(Q/2^{O-1}\right)$. Let k be a set of positive integers (representing the number of iSUEs of MNOs $\boldsymbol{O}\backslash o$ in an apartment) such that $0 \le k \le (|\boldsymbol{O}|-1)$. Then, the duration of an SC of MNO o corresponding to k can be defined by the Binomial coefficients $\mathbf{C}(O-1,k)$ of row $(O-1)$ of the left-justified Pascal's triangle [4] as follows.

$$t_{o,k} = \mathbf{C}(O-1,k)\left(Q/2^{O-1}\right) \tag{1}$$

Assume that $\boldsymbol{U}_o$ denotes a set of iSUEs of MNOs $\boldsymbol{O}\backslash o$ for an SC of MNO o such that $u_o \in \boldsymbol{U}_o = \{\boldsymbol{O}\backslash o\}$. Let P_m and P_r denote the transmission powers of an SC of MNO o corresponding to $|\boldsymbol{U}_o| = 0$ and $|\boldsymbol{U}_o| > 0$, respectively, such that P_r can be adjusted as follows.

$$P_r = \begin{cases} \alpha_1 P_m, & \text{for } |\boldsymbol{U}_o| = 1 \\ \vdots & \vdots \\ \alpha_{(|\boldsymbol{O}|-1)} P_m, & \text{for } |\boldsymbol{U}_o| = (|\boldsymbol{O}|-1) \end{cases} \tag{2}$$

Using Shannon's capacity formula, a link throughput at RB=i in TTI=t for an MNO o in bps per Hz is given by

$$\sigma_{o,t,i}\left(\rho_{o,t,i}\right) = \begin{cases} 0, & \rho_{o,t,i} < -10\,\text{dB} \\ \beta \log_2\left(1+10^{\left(\rho_{o,t,i}(\text{dB})/10\right)}\right), & -10\,\text{dB} \le \rho_{o,t,i} \le 22\,\text{dB} \\ 4.4, & \rho_{o,t,i} > 22\,\text{dB} \end{cases}$$

where $\rho_{o,t,i}$ denotes Signal-to-Interference-plus-Noise-Ratio (SINR) at RB=i in TTI=t for an MNO o in dB. β denotes the implementation loss factor.

Let P_{MC} and P_{PC} denote the transmission power of an MC and a PC, respectively, and $S_{M,o}$ and $S_{P,o}$ denote the number of MCs and PCs, respectively, of MNO o. Let M_o^{MC} denote the spectrum of an MC of MNO o. The average capacity of an MC of MNO o can be given as follows where σ and ρ are responses over M_o^{MC} RBs in $t \in \boldsymbol{T}$.

$$\sigma_o^{MC} = \sum_{t\in\boldsymbol{T}} \sum_{i=1}^{M_o^{MC}} \sigma_{o,t,i}\left(\rho_{o,t,i}\right) \tag{3}$$

However, due to the presence of Line-Of-Sight (LOS) components, low multipath fading effect, high distance-dependent path loss, small coverage, high wall and floor penetration loss, and low UE speed, the signal propagation characteristic at a high-frequency 28 GHz mmWave band does not change considerably indoors. Hence, we consider that each building has similar indoor signal propagation characteristics.

Then, by linear approximation, the average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) of all MNOs each with S_F SCs per building for the proposed DSS can be given, respectively, for L buildings by,

$$\sigma_{\mathrm{DSS}}^{\mathrm{CA}}=\sum_{o=1}^{O}\left(\begin{array}{l}\sigma_o^{\mathrm{MC}}+\\ \left(\sum_{l=1}^{L}\sum_{s=1}^{S_{\mathrm{F}}}\sum_{k=0}^{O-1}\left(\sum_{t=1}^{\left(\mathbf{C}(O-1,k)\left(\frac{Q}{2^{O-1}}\right)\right)}\sum_{i=1}^{M_{\mathrm{C}}}\sigma_{o,k,t,i}\left(\rho_{o,k,t,i}\right)\right)\right)\end{array}\right) \tag{4}$$

$$\sigma_{\mathrm{DSS}}^{\mathrm{SE}}=\sigma_{\mathrm{DSS}}^{\mathrm{CA}}\Big/\left(\left(M_{\mathrm{C}}+\sum_{o=1}^{O}M_o^{\mathrm{MC}}\right)\times Q\right) \tag{5}$$

$$\sigma_{\mathrm{DSS}}^{\mathrm{EE}}=\frac{\sum_{o=1}^{O}\left(\sum_{l=1}^{L}\left(\begin{array}{l}\left(P_{\mathrm{m}}/2^{O-1}\right)+\\ \sum_{k=1}^{(|O|-1)}\begin{array}{c}\mathbf{C}(O-1,k)\\ \left(\left(\alpha_k P_{\mathrm{m}}\right)/2^{O-1}\right)\end{array}\end{array}\right)+\left(\begin{array}{l}S_{\mathrm{P},o}P_{\mathrm{PC}}+\\ S_{\mathrm{M},o}P_{\mathrm{MC}}\end{array}\right)\right)}{\left(\sigma_{\mathrm{DSS}}^{\mathrm{CA}}/Q\right)}$$

(6)

In SESA, let each MNO be allocated to an equal amount of spectrum of M RBs. The system-level average capacity, SE, and EE of all MNOs for SESA can be given, respectively, by

$$\sigma_{\mathrm{SESA}}^{\mathrm{CA}}=\sum_{o=1}^{O}\left(\sigma_o^{\mathrm{MC}}+\sum_{l=1}^{L}\left(\sum_{s=1}^{S_{\mathrm{F}}}\sum_{t\in\boldsymbol{T}}\sum_{i=1}^{M}\sigma_{o,l,s,t,i}\left(\rho_{o,l,s,t,i}\right)\right)\right) \tag{7}$$

$$\sigma_{\mathrm{SESA}}^{\mathrm{SE}}=\sigma_{\mathrm{SESA}}^{\mathrm{CA}}\Big/\left(\left(M_{\mathrm{C}}+\sum_{o=1}^{O}M_o^{\mathrm{MC}}\right)\times Q\right) \tag{8}$$

$$\sigma_{\mathrm{SESA}}^{\mathrm{EE}}=\sum_{o=1}^{O}\left(\begin{array}{l}\sum_{l=1}^{L}\sum_{s=1}^{S_{\mathrm{F}}}P_{\mathrm{m}}+\\ \left(S_{\mathrm{P},o}P_{\mathrm{PC}}\right)+\left(S_{\mathrm{M},o}P_{\mathrm{MC}}\right)\end{array}\right)\Big/\left(\sigma_{\mathrm{SESA}}^{\mathrm{CA}}/Q\right) \tag{9}$$

IV. PERFORMANCE EVALUATION AND COMPARISON

Table I shows selected parameters and assumptions used for the performance evaluation. However, the detailed simulation parameters and assumptions can be found in [2]. Using (4)-(9) and Table I, Figure 2 shows average capacity, SE, and EE responses for the proposed DSS and traditional SESA techniques. From Figure 2(a), it can be found that proposed DSS improves SE by about 2.64 times and EE by about 74.28%, respectively over that of the traditional SESA. The similar outperformance in SE and EE can be found in Figures 2(b)-2(c) over that of SESA with the variation of L.

TABLE I. DEFAULT PARAMETERS AND ASSUMPTIONS

Parameters and Assumptions	Value
Spectrum bandwidth	200 MHz (28 GHz) and 40 MHz (2 GHz)
Number of MNOs, Transmission direction	4, downlink
P_{m}, CCI threshold, SCs per building	19 dBm, $0.3P_{\mathrm{m}}$, 48

The Sixth-Generation (6G) mobile system is expected to offer SE of 370 bps/Hz and EE of 0.3 uJ/bit [5]. Using Figure 2(b), the minimum values of L required by DSS and SESA are 9 and 32, respectively, to satisfy the above SE and EE requirements for 6G. Hence, DSS requires the reuse of the countrywide 28 GHz spectrum to 71.87% fewer buildings than that of SESA.

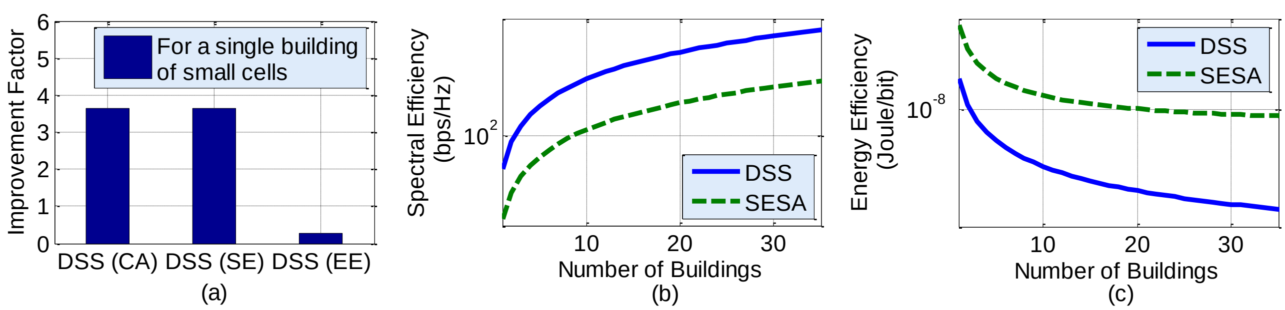

Figure 2. (a) Average capacity, SE, and EE improvement factors of DSS over that of SESA for L=1. (b) SE and (c) EE of DSS and SESA techniques for L>1.

V. CONCLUSION

In this paper, we have presented a Dynamic Spectrum Sharing (DSS) technique to share the countrywide full 28 GHz spectrum with in-building SCs of each MNO by controlling the transmission power of SCs. The proposed DSS has been detailed, and its outperformance over the traditional SESA in terms of average capacity, SE and, EE has been shown.

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