A New Paradigm for Spectrum Allocation in Millimeter-Wave Systems

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Abstract—**The traditional static and dedicated allocation of a portion of the spectrum specified for a country suffers from low spectrum availability and utilization for a Mobile Network Operator (MNO). To overcome these constraints, in this paper, we present an idea of a new technique for the spectrum allocation called Countrywide Full Spectrum Allocation (CFSA) that considers a dynamic allocation of the countrywide full millimeter-wave spectrum to each MNO to operate its in-building small cells subject to the co-channel interference management for a certain renewed-term. We present CFSA comprehensively, highlighting its rationale, significance, major concern, possible solution, and performance evaluation with respect to the traditional static spectrum allocation technique.**

Keywords-millimeter-wave; small cell; mobile network operator; spectrum allocation; spectrum utilization; countrywide.

I. INTRODUCTION

A. Background

The radio spectrum in mobile communication systems is one of the most critical requirements. Over time, though the demand of mobile users in terms of data rate and volume increases due to the increased use of rich multimedia services, the available spectrum to serve user demands allocated to a Mobile Network Operator (MNO) has not been increased proportionately (Saha [1]). As this trend continues to grow, the gap between the required spectrum to serve user demands and the spectrum available for an MNO continues to increase accordingly. Another major reason for the scarcity of spectrum goes to how the spectrum specified for a country is allocated to its MNOs. More specifically, traditionally, a portion of the countrywide spectrum is allocated to each MNO exclusively in an equal amount (in most cases) and a static manner for the long term.

However, the number of users of one MNO differs from another and so does their required spectrum. This causes an MNO with more users to experience insufficiency of the spectrum, whereas the other, with fewer users, to waste part of its allocated spectrum. Moreover, irrespective of the number of users of each MNO, the user traffic demand of one MNO varies much from another in time and space. But, due to the static and dedicated use of spectrum by each MNO over a large coverage, a significant amount of its allocated spectrum may be either unused or underutilized (Hasan et al. [2]). Hence, such a static and dedicated allocation of a portion of the full spectrum specified for a country to each MNO is no longer considered sufficient to address its ever-increasing user demands (Saha [3]), as well as efficient to utilize the allocated spectrum, particularly in urban multistory buildings as most data is generated in such indoor environments.

B. Related Work

Numerous approaches, namely spectrum aggregation, trading, sharing, and reusing have been proposed in the existing literature to increase the amount, as well as the utilization of the spectrum. For example, Yuan et al. [4] have analyzed the key challenges of realizing carrier aggregation techniques, whereas Park et al. [5] have evaluated the performances of carrier aggregation schemes in Long-term Evolution-Advanced systems. Further, Xing et al. [6] have considered spectrum trading in the context of multiple sellers and multiple buyers, whereas Niyato et al. [7] have proposed a scheme for selling the spectra of multiple primary users to multiple secondary users.

For spectrum sharing, Saha [8] has proposed a technique to share both licensed and unlicensed spectra with small cells, whereas Attiah et al. [9] have studied spectrum sharing approaches in millimeter-wave systems. Likewise, Joshi et al. [10] have proposed an analytical model to reuse the microwave spectrum, whereas Saha [11] has proposed an analytical model to reuse the 28 GHz millimeter-wave spectrum in a building of Small Cell Base Stations (SBSs). However, the above approaches can be avoided if the countrywide full-spectrum is made available to each MNO, as opposed to just a portion of it in the traditional static spectrum allocation technique, to ensure large spectrum availability, as well as efficient utilization of the allocated spectrum, to serve a large volume of indoor data at high rates for the existing and upcoming mobile networks.

C. Organization

To address the above-mentioned issues, we propose a technique for allocating the countrywide full millimeter-wave spectrum in Section II. In Section III, major concerns (e.g., co-channel interference) and possible solutions of the proposed technique are discussed. We evaluate the performance of the proposed technique in Section IV and conclude the paper in Section V.

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II. PROPOSED TECHNIQUE

The microwave spectrum, particularly below 3 GHz is almost occupied, and the millimeter-wave spectrum has been considered as a potential candidate for the Fifth-Generation (5G) and beyond mobile systems. Hence, to overcome these aforementioned constraints associated with the traditional static and dedicated spectrum allocation technique, in this paper, we present a new idea for the millimeter-wave spectrum allocation called countrywide full spectrum allocation (CFSA) stated as follows.

Each MNO of a country is allocated dynamically to the full millimeter-wave spectrum specified for the country to operate its in-building small cells subject to managing Co-Channel Interference (CCI) for a certain renewed-term t_r*. The spectrum licensing fee for each MNO is updated in accordance with the number of its subscribers for each term.* Hence, the proposed CFSA technique ensures the availability of a large amount of spectrum by allocating the countrywide full (instead of a portion) millimeter-wave spectrum, as well as an efficient spectrum utilization by allowing dynamic and flexible (instead of static and dedicated) access to each MNO. Moreover, as opposed to being bound to pay for the unused spectrum with few users, an MNO can pay only for the amount of spectrum that it uses to serve user demands at t_r, resulting in reducing the cost per unit capacity (i.e., bps).

Besides, to consider the dynamic number of users of MNOs, each SBS of all MNOs in an apartment of a building can keep sensing to detect the status of the shared full countrywide spectrum usage. Based on the CCI avoidance in time-domain, frequency-domain, or power-domain, each SBS updates the amount of time, spectrum, or transmission power, respectively. In this regard, depending on the maximum allowable control signaling overhead generated due to the coordination, SBSs either per apartment, per floor, or per building basis can form a cluster to coordinate with each other to update the CCI status locally in a distributed manner. Moreover, to detect the usage of the shared full spectrum, both reactive and proactive spectrum sensing approaches can be applied. In the reactive approach, an MNO performs the spectrum sensing mechanism to detect the usage on the shared spectrum, whereas in the reactive approach, based on the knowledge of the traffic model of User Equipments (UEs) of other MNOs $\boldsymbol{O} \backslash o$, the arrival of UEs can be predicted to update beforehand the usage of the shared countrywide full spectrum by an SBS of MNO o, where $\boldsymbol{O}$ denotes a set of MNOs in a country such that $o \in \boldsymbol{O}$.

III. MAJOR CONCERN AND POSSIBLE SOLUTION

A major concern of the proposed technique is that CCI may be generated when in-building small cells of more than one MNO attempt to access the same spectrum simultaneously. However, such CCI can be managed either in time, frequency, and power domains. In time-domain and frequency-domain, CCI can be avoided (Fig.1(b)) by allocating small cells of different MNOs in a different time interval (e.g., a transmission time interval of 1 ms) and frequency range (e.g., a resource block of 180 kHz) of the spectrum, respectively, using techniques such as time-domain and frequency-domain Enhanced Intercell Interference Coordination (eICIC) (Lopez-Perez et al. [12]; Saha and Aswakul [13]).

Recall that each MNO pays the spectrum licensing fee based on its number of subscribers for term t_r. So, the optimal value of time and frequency for an SBS of an MNO o to serve its user traffic can be derived as the ratio of the number of subscribers N_o of an MNO o to the sum of the total number of subscribers of MNOs $\boldsymbol{O} \backslash o$ (including those of MNO o) given that UEs corresponding to MNOs $\boldsymbol{O} \backslash o$ are present within the coverage of SBS of MNO o and each MNO has exactly one SBS in each apartment that can serve only one UE at a time (Fig.1(b)). For example, in time-domain eICIC, the optimal value of time in terms of the number of Transmission Time Intervals (TTIs) for an MNO o at any Almost Blank Subframe (ABS) Pattern Period (APP) of duration T_A in TTIs is given by,

$$T_o = \left\lceil \left(\left(N_o \Big/ \sum_{o=1}^{O} \left(1_{\varphi_o} \left(N_o \right) \times N_o \right) \right) \times T_A \right) \right\rceil \tag{1}$$

where $\varphi_o \in \{N_1, N_2, N_3, N_4\}$. $1(\cdot)$ is defined such that $1(\cdot) = 1$ if N_o exists in the set φ_o ; otherwise, $1(\cdot) = 0$. Similarly, following (1), we can find the amount of spectrum for MNO o in a TTI in frequency-domain eICIC.

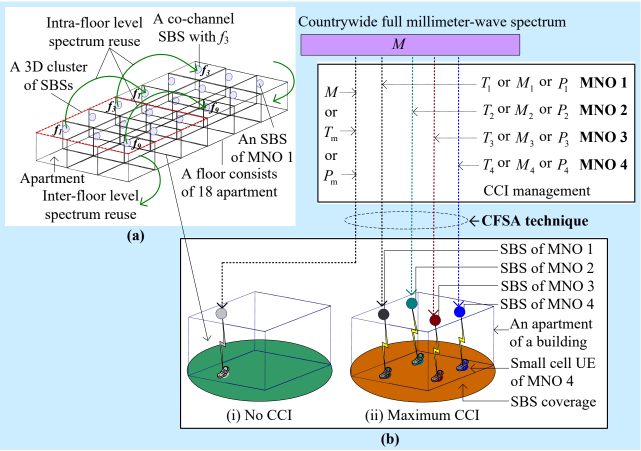

Figure 1. (a) A floor of a multistory building for 3D clustering of SBSs, (b) Illustration of the proposed CFSA technique. T_o , M_o , and P_o denote, respectively, operating time, spectrum, and power in time-domain, frequency-domain, and power-domain corresponding to MNOs $o \in \boldsymbol{O} = \{1,2,3,4\}$.

Further, in power-domain (Fig.1(b)), using cognitive radio access, such as interweave and underlay spectrum access techniques, the transmission power of an SBS can be controlled to manage CCI. More specifically, using the interweave spectrum access, an SBS of an MNO o can be allowed to serve its user traffic at the maximum power as long as no UE of other MNOs $\boldsymbol{O}\backslash o$ exists in the same apartment. If otherwise, the SBS of MNO o stops serving its users immediately by switching its transmission power off. Likewise, using the underlay spectrum access, an SBS of an MNO o can transmit simultaneously on the countrywide full spectrum by reducing its transmission power to a predefined CCI threshold level if a UE of other MNOs $\boldsymbol{O}\backslash o$ exists in the same apartment as that of an SBS of MNO o. Hence, based on the presence of a UE of other MNOs $\boldsymbol{O}\backslash o$, using a hybrid interweave-underlay spectrum access, CCI can be managed.

Let $P_{\max}$ and P_{red} denote, respectively, the maximum transmission power and the reduced transmission power of an SBS of any MNO o when operating under the interweave and underlay access techniques such that $P_{\max} > P_{\text{red}}$. Then, the transmission power of an SBS of MNO o is given by

$$P_o = \left\{ \begin{array}{ll} P_{\max}, & \text{for interweave (if no UE of MNOs } \boldsymbol{O} \setminus o \text{ exists)} \\ P_{\text{red}}, & \text{for underlay (if a UE of MNOs } \boldsymbol{O} \setminus o \text{ exists)} \end{array} \right\} \tag{2}$$

Note that, by exploiting the spatial domain, the countrywide full spectrum can be reused to in-building SBSs of an MNO o to increase the achievable capacity and spectrum utilization even further. For example, following Saha [14], by forming a 3-Dimensional (3D) cluster of SBSs in a building of an MNO o subject to satisfying a minimum CCI threshold both in the intra-floor, as well as inter-floor, levels, the same spectrum can be reused for each 3D cluster, as shown in Fig.1(a). Further, due to the high external wall penetration loss of a building for millimeter-wave signals, the countrywide full spectrum can be reused to SBSs of MNO o in adjacent buildings resulting in improving system-level capacity and spectrum utilization further. The detailed modeling of the 3D clustering of SBSs can be found in Saha [14].

IV. PERFORMANCE EVALUATION

We consider a simple example to evaluate the outperformance of CFSA, as follows. Assume that four MNOs are operating in a country such that $o \in \boldsymbol{O} = \{1,2,3,4\}$ with a subscriber base of 40%, 30%, 20%, and 10%, respectively, of the total number of subscribers countrywide at t_r. Let M=200 MHz denote the countrywide full millimeter-wave spectrum, which is allocated to each MNO based on its aforementioned subscriber base. Considering applying the frequency-domain CCI avoidance, the spectra allocated to MNOs 1, 2, 3, and 4 are given by 80 MHz, 60 MHz, 40 MHz, and 20 MHz, respectively. Assume that the millimeter-wave link quality of each UE is given by 3 bps/Hz.

Note that the number of Resource Blocks (RBs) corresponding to 80 MHz for MNO 1 is given by 400 where an RB is equal to 180 kHz. Consider that the total observation time T_m=8 TTIs where each TTI equals to 1 ms. Also, Shannon's capacity formula is given by $\sigma_{o=1} = W \log_2\left(1+\text{SINR}\right)$ where W denotes bandwidth, SINR defines Signal-to-Interference-Plus-Noise Ratio, and $\log_2\left(1+\text{SINR}\right)$ denotes link quality.

Now, using Shannon's capacity formula, the capacity and Spectral Efficiency (SE) of MNO 1 when UEs of all MNOs $\boldsymbol{O}\backslash o$=1 are present with a small cell in each apartment of MNO 1 in a building are given by 1.728 Gbps (i.e., $\left(400\,\text{RBs} \times 0.18\,\text{MHz/RB} \times 3\,\text{bps/Hz} \times 8\,\text{ms}\right)$) and 3 bps/Hz (i.e., $\left(1.728\,\text{Gbps} / \left(400\,\text{RBs} \times 0.18\,\text{MHz/RB} \times 8\,\text{ms}\right)\right)$), respectively. Following the same procedure, the capacity and SE of MNO 1 are given by 4.32 Gbps and 7.5 bps/Hz, respectively, when no UE of MNOs $\boldsymbol{O}\backslash o$=1 is present with a small cell in each apartment of MNO 1 (Fig.1(b)). However, when applying the Traditional Static Spectrum Allocation (TSSA) technique, by assuming that each MNO is allocated to an equal amount of 50 MHz spectrum, using the same procedure as above, the capacity and SE are given by 1.08 Gbps and 3 bps/Hz, respectively. These show an outperformance in capacity and SE of 60% and 0% for the maximum CCI, and 300% and 150% for no CCI of CFSA over TSSA. Hence, CFSA improves the capacity ranging from 60% to 300%, as well as the SE ranging from 0% to 150%, over TSSA.

Now, assume that due to a high floor penetration loss, a 3D cluster comprises 9 SBSs per floor each having 18 apartments of a 10-story building. If we consider reusing the countrywide full spectrum to each 3D cluster of SBSs of MNO 1, it can be reused 20 times to SBSs in the building. Since the capacity is directly proportional to the spectrum reuse factor, and the allocated spectrum to MNO 1 of 80 MHz does not change, the above capacity and SE improve by 20 times, irrespective of the level of CCI.

V. CONCLUSION AND FUTURE WORK

In this paper, we have presented an idea of allocating a countrywide full millimeter-wave spectrum to each MNO to increase the spectrum availability and utilization. We have broadly detailed the proposed technique and shown its outperformance in terms of capacity and spectral efficiency over the traditional static spectrum allocation technique. The proposed idea needs extensive study for its concrete realization. In this regard, a good starting point is to justify the possible solutions discussed in this paper to address the major concern of the proposed idea. More specifically, it is necessary to elaborate and develop techniques to manage co-channel interference in time, frequency, and power domains when allocating the full millimeter-wave spectrum to each MNO in a country, which we consider carrying out as part of our future work.

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