Spectrum Reuse in the Terahertz Band for In-building Small Cell Networks

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***Abstract*—In this paper, we present an analytical model to reuse spectrum in the Terahertz (THz) band in small cells located within a building. We characterize Co-Channel Interference (CCI) in the 140 GHz band and derive a minimum distance between co-channel small cells subject to satisfying predefined CCI interference constraints in both intra-floor and inter-floor levels. The set of small cells in both intra-floor and inter-floor levels constitute a 3-Dimensional (3D) cluster of small cells. The whole THz spectrum allocated to a Mobile Network Operator (MNO) can be reused to small cells of each cluster. We derive system-level average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) metrics for an arbitrary number of *L* buildings of small cells located over a macrocell coverage. With extensive numerical and simulation results and analyses, we show that the 3D clustering of small cells in a building and reusing the same spectrum in the 140 GHz band to each cluster improve both the SE and EE performances. Further, it is shown that the expected SE and EE requirements for the future Sixth-Generation (6G) mobile networks can be achieved by reusing the spectrum in a fewer number of buildings of small cells than that required when no spectrum reuse is considered.**

Keywords—6G; clustering; energy efficiency; in-building; small cell; spectral efficiency; spectrum reuse; THz band.

I. INTRODUCTION

Radio spectrum in mobile wireless communications is scarce and very costly. A direct, yet effective, way to improve the network capacity of a Mobile Network Operator (MNO) is to increase the system bandwidth by aggregating spectra in different bands. In this regard, due to the availability of large spectrum availability, high-frequency spectra in the range of millimeter-wave (mmWave) bands and Terahertz (THz) bands are considered to operate small cells deployed within a building. Even though, the Fifth-Generation (5G) mobile network has been rolled out in many countries in several mmWave spectrum bands, including 28 GHz and 39 GHz, the future Sixth-Generation (6G) is expected to operate in even higher frequencies such as THz bands. Due to their operational and signal propagation characteristics, including high distant-dependent path loss, low transmit power, small coverage, and presence of Line-Of-Sight (LOS) components, both mmWave and THz bands are suitable to serve indoor coverage.

Another major approach to improve the network capacity is to reuse the same spectrum spatially more than once. In this regard, due to high penetration losses from external and internal walls, as well as floors in a building, the high-frequency spectrum can be reused suitably by forming a 3-Dimensional (3D) cluster of small cells subject to managing Co-Channel Interference (CCI) between co-channel small cells. The whole spectrum can be reused to small cells per 3D cluster. However, comprehensive modeling of interference, as well as clustering of small cells, for reusing spectrum in them under the in-building scenario are not obvious. To the best of our knowledge, we first addressed these issues by modeling CCI and defining a minimum distance between co-channel small cells in a building in both intra-floor and inter-floor levels to develop a 3D cluster of small cells in order to reuse the same spectrum in each cluster in the 2 GHz microwave band Saha [1]. Likewise, in Saha [2], we dealt with managing CCI between co-channel small cells in the 28 GHz and 60 GHz mmWave bands to reuse both spectra in each 3D cluster of small cells. Due to considerable differences in operational requirements and signal propagation characteristics from the microwave and mmWave bands, following the continuation in Saha [1] and Saha [2], in this paper, we model CCI in the 140 GHz THz band to define a 3D cluster of in-building small cells in order to reuse the THz spectrum of an MNO in each 3D cluster.

In doing so, firstly, we discuss the system architecture and 140 GHz, indoor loss model, in Section II. We then present in brief CCI in both intra-floor level and inter-floor levels of a building and deduce minimum distances between co-channel small cells in both levels. A 3D cluster of small cells is then defined subject to satisfying both intra-floor and inter-floor interference constraints set by an MNO. The whole spectrum in the 140 GHz band is then reused to each 3D cluster of small cells. We derive system-level average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) metrics in Section III. In Section IV, we define parameters and assumptions, evaluate the impact of 3D clustering of in-building small cells, and compare the system-level SE and EE performances of the MNO with the corresponding expected requirements for the 6G mobile networks. We conclude the paper in Section V.

II. SYSTEM ARCHITECTURE AND THZ INDOOR LOSS MODEL

A. System Architecture

We consider a simple system architecture of an MNO, i.e., MNO 1, in a country as shown in Figure 1(a), which has three types of Base Stations (BSs), including Macrocell BS (MBS), Picocell BS (PBS), and Small cell BS (SBS). MBSs and PBSs operate in the 2 GHz spectrum, whereas all SBSs located in buildings are operated in the 140 GHz spectrum. Figure 1(a) also shows the placement of SBSs at the center of the ceiling of each apartment in a building. Each SBS serves one User Equipment (UE) at a time. An illustrative clustering in the inter-floor level (a single floor) and intra-floor level (nine

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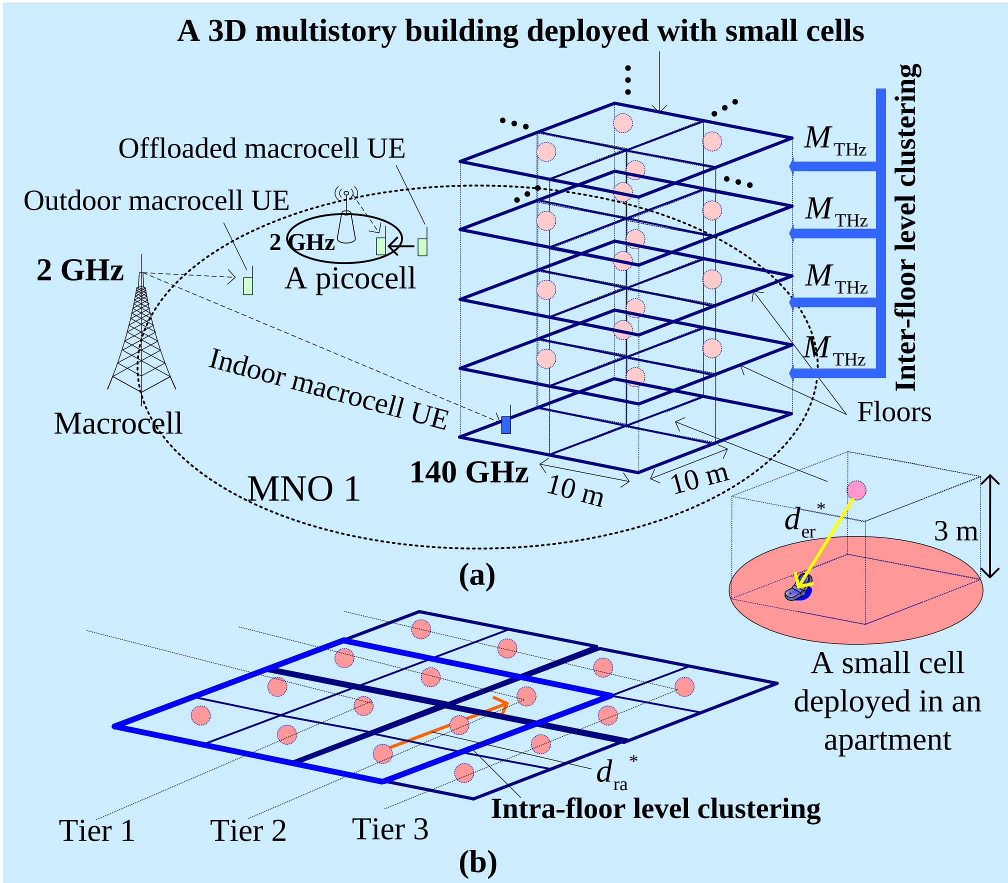


Figure 1. (a) an illustration of the system architecture of MNO 1 with a multistory building of small cells to reuse 140 GHz spectrum. (b) Intra-floor level clustering of small cells. Each circle represents a small cell in an apartment.

apartments) is shown in Figures 1(a) and 1(b), respectively. We discuss clustering in more detail in Section III.

B. 140 GHz Indoor Loss Model

1) Indoor path loss model: We consider the LOS path loss model for indoor THz communications in the 140-150 GHz band such that the average path loss at a distance d can be expressed as follows [3].

$$PL[d] = PL[d_o] + 10\gamma \log_{10}(d/d_0) + X_\Delta \quad (1)$$

where, $PL(d_0)$ denotes the path loss at the reference distance $d_0 = 0.35$ m (i.e., 0.5 m with 0.15 m is compensated for the waveguides [3]). X_Δ in dB is a zero-mean Gaussian distributed random variable with a standard deviation $\Delta = 0.5712$ dB. $\gamma = 2.117$ denotes path loss exponent [3].

Putting these above values in (1) $PL[d]$ can be expressed at the 140 GHz as follows and is proved in Proof 1.

$$PL[d] = 75.89 + 21.17\log_{10}(d) + X_\Delta \quad (2)$$

Proof 1: We know, $PL[d_0] = 10\log_{10}(4\pi d_0 f/c)$

$\gg PL[d_0] = 20\log_{10}(d_0) + 20\log_{10} f\,(\text{Hz}) - 147.55$

$\gg PL[d_0] = 32.44 + 20\log_{10}(d_0) + 20\log_{10} f\,(\text{GHz})$

For $f = 140$ GHz, we can write the following.

$\gg PL[d_0] = 32.44 + 20\log_{10}(d_0) + 20\log_{10}(140)$

$\gg PL[d_0] = 75.36 + 20\log_{10}(d_0)$

Now, using (1), and putting $d_0 = 0.35$ m and $\gamma = 2.117$, we can find the following.

$$PL[d] = 75.36 + 20\log_{10}(0.35) + (10\times 2.117)\log_{10}(d/0.35) + X_\Delta$$

$$PL[d] = 66.241 + 21.17\log_{10}(d) + 9.65 + X_\Delta$$

$$PL[d] = 75.89 + 21.17\log_{10}(d) + X_\Delta \qquad \blacksquare$$

2) 140 GHz floor attenuation loss model: The floor penetration loss is not linear and decreases with an increase in the number of floors. Moreover, the floor attenuation loss is frequency-dependent and increases with an increase in frequency. In general, experimental signal propagation studies and results in the THz band are very limited in the existing literature. Hence, if we consider a reinforced concrete floor, according to [4], the floor attenuation loss is above 50 dB for the first floor at 28 GHz. Since the floor attenuation loss increase with an increase in frequency, the loss at 140 GHz must be higher than 50 dB for the first floor. The impact of CCI at this floor attenuation loss of more than 50 dB for the first floor at the 140 GHz is negligible in the adjacent floor, and hence we assume no CCI interference effect from one adjacent floor to another at the 140 GHz band.

III. Modeling CCI, 3D Cluster, and Spectrum Reuse in 140 GHz Band and Estimating Performance Metrics

A. Modeling CCI, Small Cell Cluster, and Spectrum Reuse in the 140 GHz Band

1) Co-channel interference modeling: Following [2], the normalized CCI at a small cell UE in the intra-floor level and inter-floor level, respectively, can be given by,

$$\alpha_{\mathrm{ra}}\left(d_{\mathrm{ra}}\right)=\left(d_{\mathrm{m}}/d_{\mathrm{ra}}\right)^{2.117} \tag{3}$$

$$\alpha_{\mathrm{er}}\left(d_{\mathrm{er}}\right)=10^{-0.1\alpha_{\mathrm{f}}\left(d_{\mathrm{er}}\right)}\times\left(d_{\mathrm{m}}/d_{\mathrm{er}}\right)^{2.117} \tag{4}$$

where $\alpha_{\mathrm{f}}\left(d_{\mathrm{er}}\right)$ denotes floor penetration loss. d_{ra} and d_{er} denote, respectively, a minimum distance between co-channel small cells to allow reusing the same spectrum to both small cells. d_{m} defines a distance from small cells corresponding to the maximum CCI experienced by a small cell UE.

Proof 2: See Section II(C) of [2] for the Proofs of (3) and (4).

2) Minimum distance estimation: Let $I_{\mathrm{m,ra}}$ and $I_{\mathrm{m,er}}$ denote, respectively, the maximum number of co-channel interferers in the intra-floor and inter-floor levels. For square-grid apartments (Figure 1(a)) per floor of a multistory building, $I_{\mathrm{m,ra}}=8$ and $I_{\mathrm{m,er}}$ is 1 and 2, respectively, for the single-sided and double-sided co-channel interferers [2]. Now, let the optimal value of the aggregate CCI set by an operator in the intra-floor and inter-floor levels are denoted as $\alpha_{\mathrm{ra,op}}$ and $\alpha_{\mathrm{er,op}}$, respectively. Let at a minimum distance $d_{\mathrm{ra}}=d_{\mathrm{ra}}^{*}$ in the intra-floor level and $d_{\mathrm{er}}=d_{\mathrm{er}}^{*}$ in the inter-floor level, $\alpha_{\mathrm{ra,op}}$ and $\alpha_{\mathrm{er,op}}$ can be satisfied, i.e., the following conditions must satisfy.

$$I_{\mathrm{m,ra}}\times\left(d_{\mathrm{m}}/d_{\mathrm{ra}}\right)^{2.117}\leq\alpha_{\mathrm{ra,op}} \tag{5}$$

$$I_{\mathrm{m,er}}\times\left(10^{-0.1\alpha_{\mathrm{f}}\left(d_{\mathrm{er}}\right)}\times\left(d_{\mathrm{m}}/d_{\mathrm{er}}\right)^{2.117}\right)\leq\alpha_{\mathrm{er,op}} \tag{6}$$

After manipulating (5) and (6), the minimum distances in the intra-floor level and inter-floor level can be expressed as follows.

$$d_{\mathrm{ra}}^{*}\geq d_{\mathrm{m}}\times\left(I_{\mathrm{m,ra}}/\alpha_{\mathrm{ra,op}}\right)^{2.117^{-1}} \tag{7}$$

$$d_{\mathrm{er}}^{*}\geq d_{\mathrm{m}}\times\left(10^{-0.1\alpha_{\mathrm{f}}\left(d_{\mathrm{er}}\right)}\times\left(I_{\mathrm{m,er}}/\alpha_{\mathrm{er,op}}\right)\right)^{2.117^{-1}} \tag{8}$$

Proof 3: See Section III of [2] for the Proofs of (7) and (8).

3) Clustering and spectrum reuse factor: Let S_{ra} and S_{er} denote the maximum number of small cells corresponding to satisfying the minimum distances d_{ra}^{*} and d_{er}^{*}, respectively, such that the size of a 3D cluster of small cells deployed across intra-floor and inter-floor levels is given by,

$$S_{\mathrm{F}}=\left(S_{\mathrm{ra}}\times S_{\mathrm{er}}\right) \tag{9}$$

Hence, for a given number of small cells $S_{\mathrm{F,tot}}$ per building, the same THz spectrum band can be reused by the number of times (i.e., Spectrum Reuse Factor) per building of small cells as given below.

$$\varepsilon=S_{\mathrm{F,tot}}/S_{\mathrm{F}} \tag{10}$$

For more information on the clustering of small cells and reuse of the same spectrum in small cells within a building, please refer to [2].

B. Estimating Performance Metrics

Let M_{GHz} and M_{THz} denote, respectively, the number of Resource Blocks (RBs) in the 2 GHz spectrum and 140 GHz spectrum where an RB is equal to 180 kHz. Let $P_{\mathrm{GHz,MC}}$, $P_{\mathrm{GHz,PC}}$, and $P_{\mathrm{THz,SC}}$ denote, respectively, the transmission power of a macrocell, a picocell, and a small cell. Then, a link throughput at RB=*i* in a Transmission Time Interval (TTI)=*t* in bps per Hz corresponding to the downlink received signal-to-interference-plus-noise ratio $\rho_{t,i}$ is given by,

$$\sigma_{t,i}\left(\rho_{t,i}\right)=\begin{cases}0, & \rho_{t,i}<-10\,\mathrm{dB}\\ \beta\log_{2}\left(1+10^{\left(\rho_{t,i}(\mathrm{dB})/10\right)}\right), & -10\,\mathrm{dB}\leq\rho_{t,i}\leq 22\,\mathrm{dB}\\ 4.4, & \rho_{t,i}>22\,\mathrm{dB}\end{cases} \tag{11}$$

where β denotes the implementation loss factor. The total capacity of all macrocell UEs in $t\in\boldsymbol{T}=\{1,2,\ldots,Q\}$ is given by,

$$\sigma_{\mathrm{MC}}=\sum_{t=1}^{Q}\sum_{i=1}^{M_{\mathrm{GHz}}}\sigma_{t,i}\left(\rho_{t,i}\right) \tag{12}$$

Now, the aggregate capacity served by a small cell in a building in $t\in\boldsymbol{T}$ over M_{THz} RBs is given by,

$$\sigma_{s}=\sum_{t\in\boldsymbol{T}}\sum_{i=1}^{M_{\mathrm{THz}}}\sigma_{t,i}\left(\rho_{t,i}\right) \tag{13}$$

Since each 3D cluster of small cells consists of S_{F} small cells in a building, and the total 140 GHz spectrum can be reused to each cluster, the aggregate capacity served by a 3D cluster of small cells in $t\in\boldsymbol{T}$ over M_{THz} RBs is given by,

$$\sigma_{3\mathrm{D}}=\sum_{s=1}^{S_{\mathrm{F}}}\sigma_{s}$$

$$\sigma_{3\mathrm{D}}=\sum_{s=1}^{S_{\mathrm{F}}}\sum_{t\in\boldsymbol{T}}\sum_{i=1}^{M_{\mathrm{THz}}}\sigma_{t,i}\left(\rho_{t,i}\right) \tag{14}$$

Using (10), since there are ε 3D clusters of small cells per building, the same 140 GHz spectrum can be reused ε times to small cells per building. Hence, the aggregate capacity served by all small cells $S_{\text{F,tot}}$, i.e., $(\varepsilon \times S_{\text{F}})$, per building is given by,

$$\sigma_{\text{THz}} = (\varepsilon \times \sigma_{\text{3D}})$$

$$\sigma_{\text{THz}} = \varepsilon \times \left(\sum_{s=1}^{S_{\text{F}}} \sum_{t \in \boldsymbol{T}} \sum_{i=1}^{M_{\text{THz}}} \sigma_{t,i}\left(\rho_{t,i}\right) \right) \tag{15}$$

Due to the high operating frequency and the low transmission power of each small cell, we consider similar indoor signal propagation characteristics for all L buildings per macrocell. Then, by linear approximation, the system-level average capacity per macrocell of MNO 1 is given by the sum of the aggregate capacity of all macrocell UEs served by the macrocell and picocells and the aggregate capacity of all small cell UEs served by small cells in L buildings. Hence, using (12) and (15), the system-level average capacity per macrocell of MNO 1 is given by

$$\sigma_{\text{CP}}(L) = \sigma_{\text{MC}} + (L \times \sigma_{\text{THz}}) \tag{16}$$

Since SE is defined as the achievable capacity per unit of spectrum bandwidth, using (16), the system-level average SE of MNO 1 in bps/Hz can be expressed as follows.

$$\sigma_{\text{SE}}(L) = \sigma_{\text{CP}}(L) / \left((M_{\text{GHz}} + M_{\text{THz}}) \times Q \right) \tag{17}$$

Now, define EE as the amount of energy required to transmit a bit of information, using (16), the system-level EE of MNO 1 in Joule/bit can be expressed as follows.

$$\sigma_{\text{EE}}(L) = \left(\begin{array}{l} (L \times S_{\text{F}} \times P_{\text{THz,SC}}) + \\ (S_{\text{P}} \times P_{\text{GHz,PC}}) + \\ (S_{\text{M}} \times P_{\text{GHz,MC}}) \end{array} \right) \Big/ \left(\sigma_{\text{CP}}(L) / Q \right) \tag{18}$$

where S_{M} and S_{P} denote, respectively, the number of macrocells and picocells in the system of MNO 1.

IV. PERFORMANCE EVALUATION AND COMPARISON

Default parameters and assumptions used for the evaluation are given in Table I. Note that due to low output power and high propagation loss, the coverage of THz signals is limited [6]. To overcome these constraints, high-gain antennas at both ends are required. Hence, following [3], we consider horn antennas at the transmitting and receiving ends each with a gain of 21 dB. Assume that $\alpha_{\text{ra,op}} = 0.3$ such that $d_{\text{ra}}^* \geq 23.58$ m, which implies that the spectrum can be reused in co-channel small cells that are away from one another by at least three apartments each having a side length of 10 m. This corresponds to an intra-floor cluster size consisting of 9 small cells. Now considering $\alpha_{\text{f}}(d_{\text{er}}) = 55$ dB and $\alpha_{\text{er,op}} = 0.1$, $d_{\text{er}}^* \geq 0.089$ m, which implies that the spectrum can be reused on each floor. So, from d_{ra}^* and d_{er}^*, we can find that a 3D cluster consists of 9 small

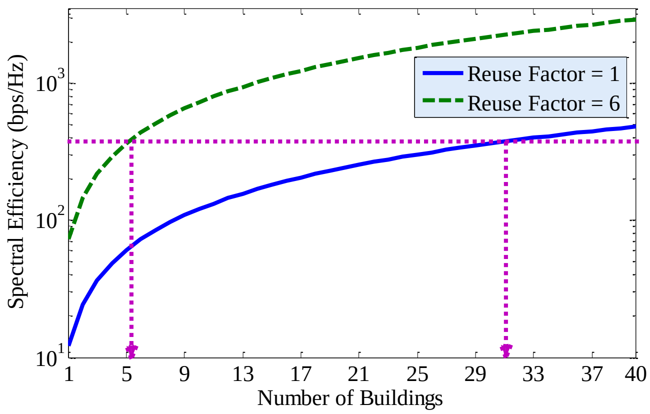
TABLE I. DEFAULT PARAMETERS AND ASSUMPTIONS

Parameters and Assumptions	Value
Cellular layout[2], Inter-Site Distance (ISD)[1,2], transmit direction	Hexagonal grid, dense urban, 3 sectors per macrocell, 1732 m, and downlink
Carrier frequency	2 GHz Non-LOS for MBSs and PBSs, 140 GHz LOS for SBSs
System bandwidth	10 MHz (for 2 GHz), 50 MHz (for 140 GHz)
Number of cells	1 MBS, 2 PBSs, 48 SBSs per building
Transmit power[1] (dBm)	46 for MBS[1], 37 for PBS[1], 10 for SBS[3]
small-scale fading model[1]	Rayleigh for 2 GHz, no small-scale fading effect for 140 GHz
Lognormal shadowing standard deviation (dB)	8 for MBS[2], 10 for PBS[1], and 0.5712 for 140 GHz LOS for SBS[3]
Path loss – MBS and a UE[1] – Indoor macrocell UE	PL(dB)=15.3 + 37.6$\log_{10}R$, R is in m
Path loss – MBS and a UE[1] – Outdoor macrocell UE	PL(dB)=15.3 + 37.6$\log_{10}R$ + L_{ow}, R is in m
Path loss – PBS and a UE[1]	PL(dB)=140.7+36.7$\log_{10}R$, R is in km
Path loss – SBS and a UE[3]	$PL(\text{dB}) = 75.89 + 21.17\log_{10}(R)$, R in m
Antenna configuration	Single-input single-output for all BSs and UEs
BS antenna gain	14 dBi for MBS[2], 5 dBi for PBS[1], 21 dB for SBS[3]
UE antenna gain	0 dBi for 2 GHz[2], 21 dB (horn antenna) for 140 GHz[3]
UE noise figure[2]	9 dB (for 2 GHz)[2], 9.56 dB (for 140 GHz)[4]
Total number of macrocell UEs	30
PBS coverage and macrocell UEs offloaded to all PBSs[1], Indoor macrocell UEs[1]	40 m (radius), 2/15, 35%
Scheduler and traffic model[2]	Proportional Fair (PF) and full buffer
Type of SBSs	Closed Subscriber Group (CSG) femtocell BSs
TTI[1] and scheduler time constant (t_c)	1 ms and 100 ms
Total simulation run time	8 ms
Building and small cell models: Number of buildings, floors per building, apartments per floor, small cells per apartment, area of an apartment	L, 6, 8, 1, 10×10 m^2

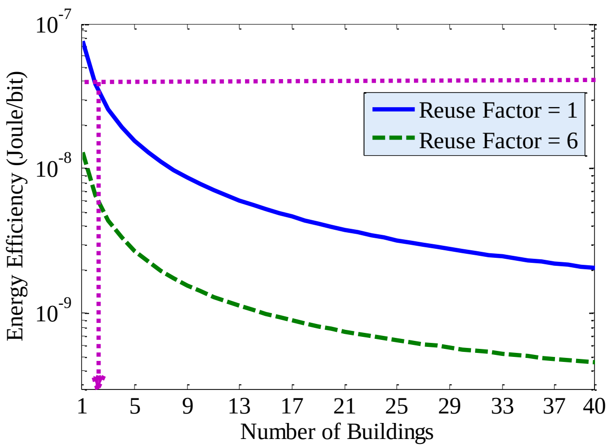
taken [1]from [7], [2]from [8], [3]from [9], [4]form [10].

cells. Hence, for a 6-story building with each floor having 9 apartments, the 140 GHz spectrum can be reused 6 times.

Figure 2 shows the SE and EE responses due to reusing 50 GHz spectrum in small cells per building in the 140 GHz band for $\varepsilon = 1$ and $\varepsilon = 6$. Clearly, it can be found that clustering small cells in the 140 GHz band and reusing the same spectrum more than once improve both SE and EE performances. Further, it is expected that the 6G mobile systems will require 10 times average SE [10] (i.e., 270-370 bps/Hz), as well as 10-100 times average EE [11] (i.e., 0.03×10^{-6} to 0.3×10^{-6} Joules/bit), of 5G mobile systems [12]-[13]. Now, from Figure 2, it can be found that the expected average SE and EE can be satisfied by reusing the spectrum to less number of buildings of small cells (i.e., L=6) than that required (i.e., L=31) when no spectrum reuse is considered.



(a)



(b)

Figure 2. (a) SE and (b) EE responses due to clustering of in-building small cells and reusing the same spectrum $\varepsilon = 6$ times in the 140 GHz band.

V. CONCLUSION

In this paper, we have presented an analytical model to reuse Terahertz (THz) spectrum to small cells of an MNO. All small cells are deployed within buildings and operate only in the 140 GHz band. Interference from one small cell to another due to reusing the 140 GHz spectrum has been modeled both intra-floor and inter-floor levels and the corresponding minimum distance between co-channel small cells have been derived. These minimum distances in the intra-floor and inter-floor level provide the size of a 3D cluster of small cells. We have derived average capacity, Spectral Efficiency (SE), and Energy Efficiency (EE) performance metrics. Extensive simulation and numerical results analyses have been carried out.

It has been found that the 3D clustering of in-building small cells, and reusing the same spectrum in the 140 GHz band to each cluster improve both the SE and EE performances. Moreover, both inter-building reuse factor and intra-building reuse factor have an impact on the overall performance improvement. Finally, we have shown that the presented model can satisfy the prospective SE and EE requirements for the Sixth-Generation (6G) networks by reusing the spectrum in less number of buildings of small cells than that required when no spectrum reuse is considered in the 140 GHz.

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