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

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Resume of the Presenter

RONY KUMER SAHA received the B.Sc. degree in electrical and electronic engineering from the Khulna University of Engineering and Technology, KUET, in 2004, the M.Eng. degree in information and communications technologies from the Asian Institute of Technology (AIT), Thailand, in 2011, and the Ph.D. degree in electrical engineering from Chulalongkorn University, Thailand, in 2017. Since 2017, he has been working as a Postdoctoral Fellow/Research Engineer with the Radio and Spectrum Laboratory, KDDI Research, Inc., Japan.

He worked as a Lecturer and later promoted to an Assistant Professor with American International University-Bangladesh, Bangladesh, AIUB, from January 2005 to August 2013. From September 2013 to July 2014, he was with East West University, Bangladesh. His current research interests include 5G and beyond ultra-dense HetNets, spectrum sharing, policy, and management in multiple communication systems, and millimeter-wave communications. He has research experiences on mobile wireless communications in universities and industries for more than ten years. He has authored about 60 peer-reviewed, reputed, and highly recognized international journal and conference papers. He also filed an international patent.

Dr. Saha served as a member of the Fronthaul Working Group, xRAN Forum, USA. He also served as a TPC member of the 2020 ICSNC and 2018 IEEE Global Communications Conference Workshops. Furthermore, he also served as the Session Chair for two sessions, namely Radio Resource Management and Aerial Networks at 2019 IEEE VTC-Fall, Hawaii, USA, as well as the 2019 IEEE International Symposium on Dynamic Spectrum Access Networks Newark, NJ, USA, for the session Spectrum Sharing in 5G. Since early 2019, he has been serving as an Associate Editor of the Engineering Journal, Thailand. He served as a Reviewer of a number of recognized journals, including IEEE Transactions on Vehicular Technology, IEEE Access, Elsevier Physical Communication, Wiley International Journal of Communication Systems, MDPI Sensors Journal, MDPI Symmetry Journal, Hindawi Mobile Information Systems, and MDPI Sustainability Journal.

Topics of Research Interests

- Terahertz and millimeter wave communications
- 5G NR-U: 5G New Radio on Unlicensed Bands
- Dynamic spectrum sharing and policy for 5G and beyond mobile networks
- Cognitive radio networks and spectrum sensing techniques
- Co-channel interference analysis, mitigation, avoidance, and cancellation strategies
- In-building small cell network planning, design and deployment
- Planning, design and development of spectrum sharing algorithm for homogeneous (mobile networks) and heterogeneous networks (mobile networks and satellite networks)
- Radio resource allocation and scheduling policy and algorithm
- Mobile MAC layer and physical layer issues
- Proof-of-concept evaluation of virtualization and Slicing of 5G radio access network (RAN)
- Cloud RAN (CRAN) in 5G era
- Fronthaul design for CRAN

Presentation Outline

- Problem Statement and Contribution
- System Architecture and Indoor Loss Model
  - Modeling Interference, 3D Cluster, and Spectrum Reuse at 140 GHz for Small Cells
  - Performance Estimation
  - Performance Evaluation and Comparison
    - Conclusion
      - References

Problem Statement and Contribution (1)

PROBLEM

Radio spectrum in mobile wireless communications is **scarce and very costly**.

(1) 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 and
- the operational and signal propagation characteristics, including high distant-dependent path loss, low transmit power, small coverage, and presence of line-of-sight (LOS) components,

OVERCOME

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.

(2) 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 then be reused to small cells per 3D cluster.

Problem Statement and Contribution (2)

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

RELATED WORK

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 in Saha [1].
- In Saha [2], we dealt with managing CCI between co-channel small cells in the 28 GHz and 60 GHz mmWave bands to reuse them in each 3D cluster of small cells.

CONTRIBUTION

Following the continuation in **Saha [1] and Saha [2]**, in this paper, we **model CCI in the 140 GHz 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**.

System Architecture and Indoor Loss Model

- We consider a simple system architecture of an MNO, i.e., MNO 1, in a country as shown in **Figure 1(a).**
- MBSs and PBSs operate in the 2 GHz spectrum,
- whereas all SBSs located in buildings are operated in the 140 GHz spectrum

140 GHz Indoor Loss Model

We consider the following **LOS path loss model** for indoor THz coverage in the **140-150** GHz

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

Also, we assume **no CCI interference effect** from one adjacent floor to another at the 140 GHz band due to high floor penetration losses at 140 GHz.

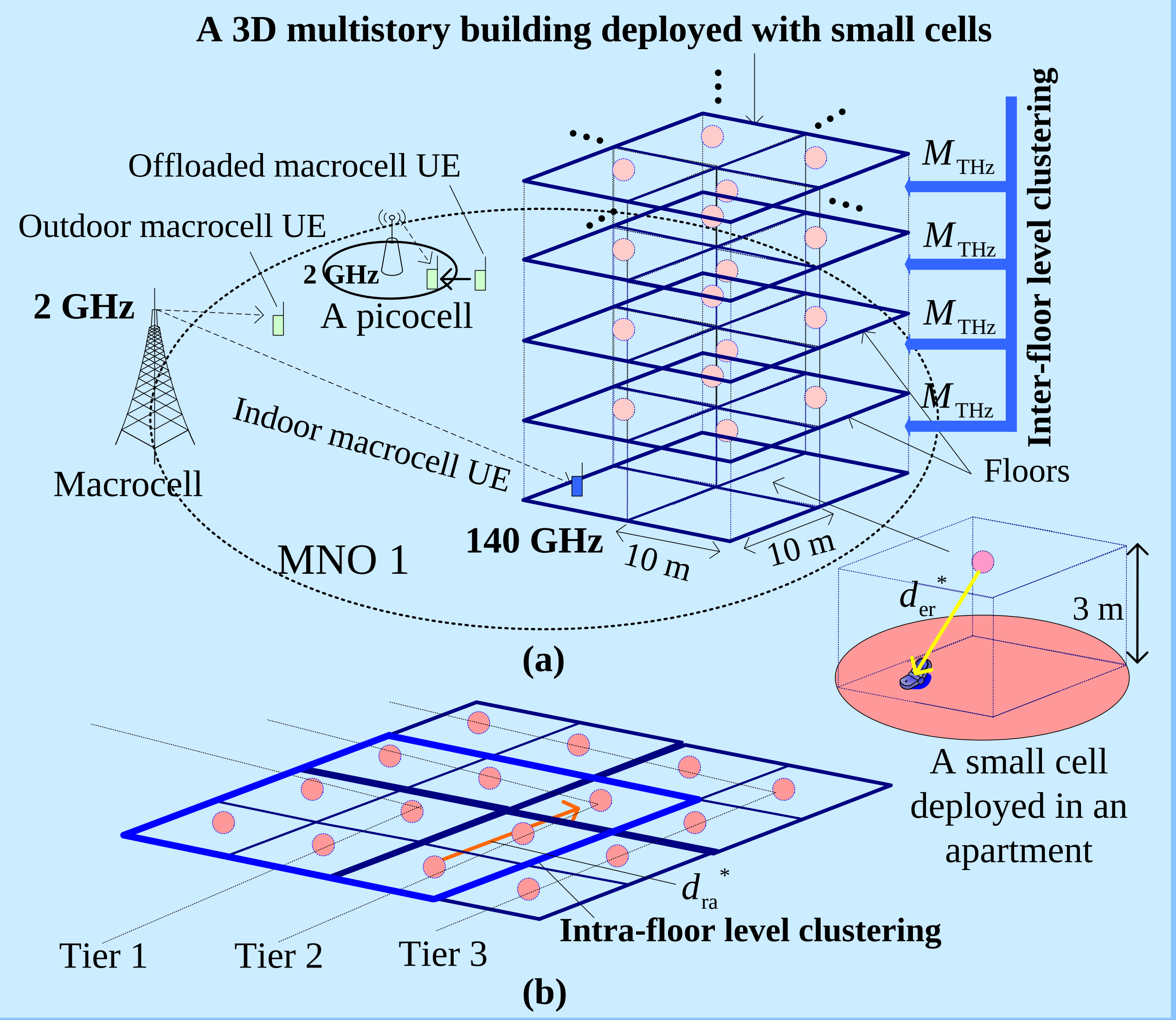

Figure 1. (a) an illustration of the system architecture of MNO 1 with a multistory building of small cells to reuse 140 GHz spectrum. (b) Intra-floor level clustering of small cells. Each circle represents a small cell in an apartment.

Modeling Interference, 3D Cluster, and Spectrum Reuse at 140 GHz for Small Cells

Co-channel interference modeling

The normalized CCI at a small cell UE in the intra-floor level and inter-floor level, respectively,

$$\alpha_{\mathrm{ra}}(d_{\mathrm{ra}}) = (d_{\mathrm{m}}/d_{\mathrm{ra}})^{2.117}$$

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

Minimum distance estimation

The minimum distances in the intra-floor level and inter-floor level can be expressed as

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

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

Clustering and spectrum reuse factor

S_{ra} denotes the maximum number of small cells corresponding to d_{ra}^{*}

S_{ea} denotes the maximum number of small cells corresponding to d_{er}^{*}

The size of a **3D cluster of small cells** deployed across intra-floor and inter-floor levels is given by

$$S_{\mathrm{F}} = (S_{\mathrm{ra}} \times S_{\mathrm{er}})$$

THz Spectrum Reuse Factor per building of small cells is given as below.

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

where $S_{\mathrm{F,tot}}$ denotes the number of small cells per building.

Performance Estimation

A link throughput at RB=i in a TTI=t in bps per Hz is given by

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

The total capacity of all **macrocell UEs**

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

The aggregate capacity served **by a small cell** in a building

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

The aggregate capacity served **by a 3D cluster** of small cells

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

The aggregate capacity served by all small cells **per building**

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

We consider similar indoor signal propagation characteristics for all L buildings per macrocell. The system-level **average capacity, SE, and EE** per macrocell of MNO 1 is given by,

$$\sigma_{\mathrm{CP}}(L)=\sigma_{\mathrm{MC}}+\left(L\times\sigma_{\mathrm{THz}}\right)$$

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

$$\sigma_{\mathrm{EE}}(L)=\begin{pmatrix}\left(L\times S_{\mathrm{F}}\times P_{\mathrm{THz,SC}}\right)+\\ \left(S_{\mathrm{P}}\times P_{\mathrm{GHz,PC}}\right)+\\ \left(S_{\mathrm{M}}\times P_{\mathrm{GHz,MC}}\right)\end{pmatrix}\Bigg/\left(\sigma_{\mathrm{CP}}(L)/Q\right)$$

Performance Evaluation and Comparison (1)

Assume that $\alpha_{\text{ra,op}} = 0.3$ => $d_{\text{ra}}^{*} \geq 23.58\ \text{m}$

This 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.**

For $\alpha_{\text{f}}(d_{\text{er}}) = 55\ \text{dB}$ => $\alpha_{\text{er,op}} = 0.1$ => $d_{\text{er}}^{*} \geq 0.089\ \text{m}$

This implies that the spectrum can be **reused on each floor**.

Hence, we can find that **a 3D cluster consists of 9 small cells**. So, for a **6-story building** with each floor having 9 apartments, the **140 GHz** spectrum can be **reused 6 times**.

Performance Evaluation and Comparison (2)

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.

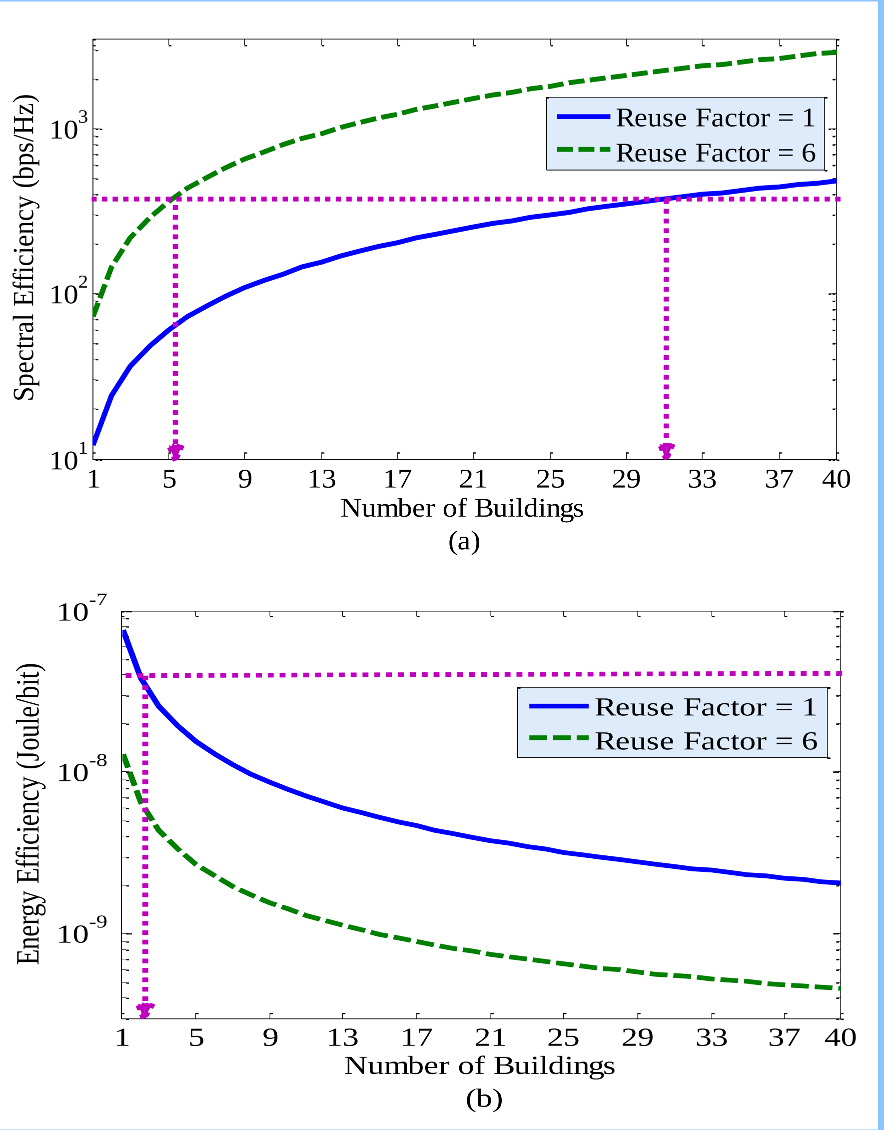

Figure 2. (a) SE and (b) EE responses due to clustering of in-building small cells and reusing the same spectrum $\varepsilon = 6$ times in the 140 GHz band.

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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Thank You …