Performance Analysis of In-building Small Cell Networks: Carrier Frequency Band Perspective

Rony Kumer Saha

Presented by
Rony Kumer Saha, Ph.D.
Radio and Spectrum Laboratory
KDDI Research, Inc. JAPAN
2-1-15 Ohara, Fujimino-shi, Saitama, 356-8502
Email: ro-saha@kddi-research.jp

KDDI Research

IARIA

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
- Assumption and Consideration
  - System Architecture
  - Problem Formulation
    - Performance Evaluation and Comparison
    - Conclusion
      - References

Problem Statement and Contribution (1)

PROBLEM

To address the scarcity of available spectrum, the **operating spectrum of small cells** of one mobile generation **shifts toward higher carrier frequencies** than that of its predecessor one.

EFFECT

- As the signal propagation characteristics vary significantly with a change in carrier frequency, the performance of small cells also varies accordingly.
- This **necessitates a deep understanding of how the channel performances** within in-building environments **vary with a change in the carrier frequency of small cells**.

RELATED WORK

Numerous studies addressed the performance evaluation of small cells in multistory buildings, mostly in terms of signal propagation measurements, at different carrier frequencies.

- Chandra **[2]** carried out propagation measurements in an indoor building environment at 900 MHz and 450 MHz.

Problem Statement and Contribution (2)

RELATED WORK

- Al-Samman, et al. **[3]** presented a comparative study of two bands, including 3.5 GHz and 28 GHz.
- Deng **[4]** presented 28 GHz and 73 GHz millimeter-wave (mmWave) propagation measurements in a typical office environment.
- Abbasi et al. **[5]** performed channel measurements and path loss modeling in the Terahertz (THz) band.

PROBLEM STATEMENT

Since the future **Sixth-Generation (6G)** network is expected to operate in **low, as well as very high, frequency bands** to address both coverage and capacity demands, instead of a certain frequency band discussed above,

a **common understanding** *of how the performance of small cells is affected with a change in the operating carrier frequency (and hence signal propagation characteristics) over a vast range, including very high THz band, is not* **obvious** *in the existing studies.*

Problem Statement and Contribution (3)

To address this concern, in this paper, we present the performance analysis of in-building small cells over a vast range of carrier frequencies as follows:

- from a **microwave band** (i.e., **2 GHz** used in the former Second-Generation (2G) up to Fourth-Generation (4G)),
- through a number of **mmWave bands** (i.e., **28 GHz** used in the existing Fifth-Generation (5G) and **60 GHz** expected to be used in the enhanced version of the existing 5G),
- to a **THz band** (i.e., **140 GHz**) proposed to be used in the upcoming 6G mobile networks.

More specifically, we contribute the following:

- We vary the carrier frequency of small cells as aforementioned and **derive** the corresponding average capacity, Spectral Efficiency (SE), Energy Efficiency (EE), and throughput per in-building small cell user performance metrics.
- We carry out extensive simulation results and evaluate these performance metrics.
- Finally, we present a performance comparison against both SE and EE requirements expected for the 6G mobile networks.

Assumption and Consideration

Because of the occurrence of high small-scale fading effects, the Non-Line-of-Sight (NLOS) channel model for the 2 GHz microwave band, whereas the Line-of-Sight (LOS) channel model for the 28 GHz and 60 GHz mmWave bands and the 140 GHz band, are considered and given for a distance *d* in m in Table I.

Table I. Channel models for different carrier frequency bands.

Channel Model			**Value**
Path loss	Carrier Frequency	2 GHz[1,2]	$127+30\log_{10}(d/1000)$
		28 GHz[5]	$61.38+17.97\log_{10}(d)$
		60 GHz[3]	$68+21.7\log_{10}(d)$
		140 GHz[4]	$75.89+21.17\log_{10}(d)$
Lognormal Shadowing standard deviation (dB)			10 (for 2 GHz)[1,2], 9.9 (for 28 GHz)[5], 0.88 (for 60 GHz)[3], and 0.5712 (for 140 GHz)[4]
Small-scale fading model			Frequency selective Rayleigh for 2 GHz[1], no small-scale fading effect for 28 GHz[5], 60 GHz[3], and 140 GHz[4]

taken [1]from [6], [2]from [7], [3]from [8], [4]from [5], [5]from [9].

System Architecture

- A simple system architecture for the performance evaluation is considered as shown in Figure 1.
- A number of Macrocell User Equipments (UEs) are considered indoors and all other outdoor Macrocell UEs (MUEs) are either served by the MBS or offloaded to nearby PBSs.
- However, all Small Cell UEs (SUEs) are served only by in-building SBSs.
- Both MBSs and PBSs operate in the 2 GHz band, whereas all SBSs operate at either 2 GHz, 28 GHz, 60 GHz, or 140 GHz band at any time.

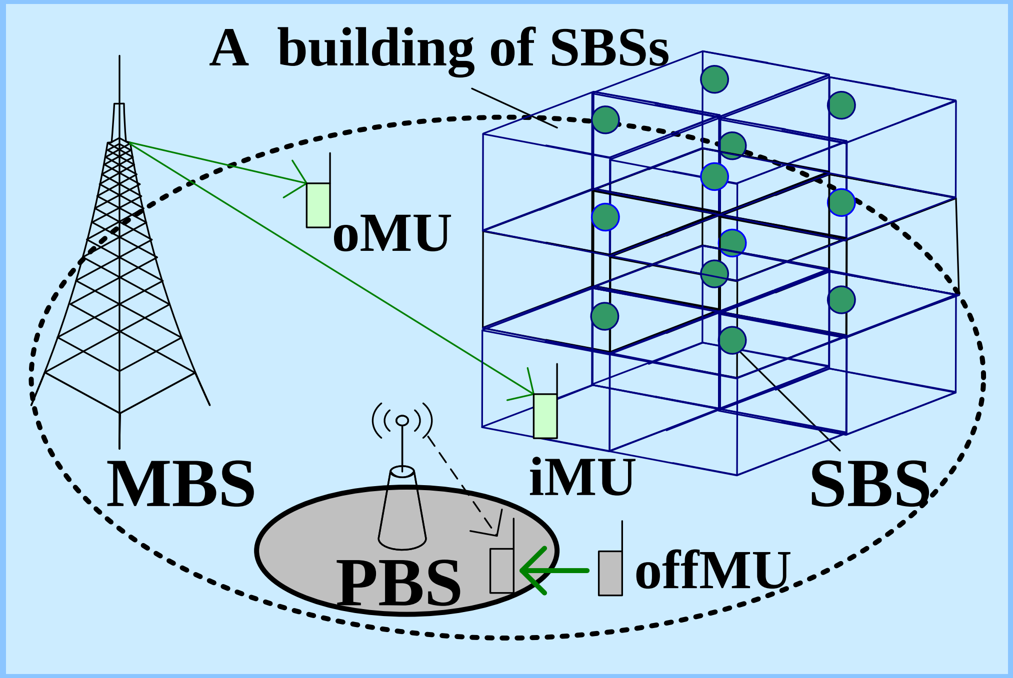

Figure 1. System architecture. oMU, iMU, and offMU define outdoor, indoor, and offloaded MUEs, respectively.

Problem Formulation

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

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

The total capacity of all MUEs

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

The aggregate capacity served by all SBSs in a single building when operating only in the **2 GHz band** is then given by,

$$\sigma_{\text{SU},2,L=1}=\sum_{s=1}^{S_{\text{F}}}\sum_{t\in\boldsymbol{T}}\sum_{i=1}^{M_2}\sigma_{t,i}\left(\rho_{t,i}\right)$$

We consider similar indoor signal propagation characteristics for all L buildings per macrocell

The system-level **average capacity, SE, and EE** per macrocell of the MNO when SBSs operate in the **2 GHz band** are given by

$$\sigma_{2,L>1}=\sigma_{\text{MU}}+\left(L\times\sigma_{\text{SU},2,L=1}\right)$$

$$\gamma_{2,L>1}=\sigma_{2,L>1}\Big/\left(\left(M_{\text{MC}}+M_2\right)\times Q\right)$$

$$\varepsilon_{2,L>1}=\left(\begin{matrix}\left(L\times S_{\text{F}}\times P_2\right)+\\ \left(S_{\text{M}}\times P_{\text{M}}+S_{\text{P}}\times P_{\text{P}}\right)\end{matrix}\right)\Bigg/\left(\sigma_{2,L>1}/Q\right)$$

Assume that each SBS can serve one SUE at any time in all carrier frequencies. Then the **average throughput per SUE** when SBSs operate in the **2 GHz band** can then be expressed

$$\sigma_{2,s}=\sigma_{\text{SU},2,L=1}\big/S_{\text{F}}$$

Following the above procedure for the 2 GHz band, the system-level average capacity, SE, EE, and average throughput per SUE when small cells operate in the 28 GHz, 60 GHz, and 140 GHz can also be derived.

Performance Evaluation and Comparison (1)

Default simulation parameters and assumptions for SBSs are given in Table II. For MBSs and PBSs, detailed parameters and assumptions can be found in [10].

We assume that each MNO in a country is allocated to a dedicated spectrum in the 2 GHz, 28 GHz, and 140 GHz bands such that no CCI effect is experienced by any in-building SBS due to operating in the spectrum by SBSs of another MNO.

Also, it is assumed that no CCI effect is experienced by any in-building SBS when operating in the 60 GHz band due to coexisting with the IEEE 802.11ad/ay, also termed as Wireless Gigabit (WiGig), access points.

Table II. Default parameters and assumptions

Parameters and Assumptions	**Value**
Transmit direction	Downlink
SBS operating bandwidth	50 MHz (for each carrier frequency)
Number of RBs in the SBS bandwidth	250 (for each carrier frequency)
Number of SBSs	48 (per building)
Transmission power (dBm)[7]	10 (for each carrier frequency)
Antenna configuration	Single-input single-output for all SBSs and SUEs
SBS antenna gain[7]	21 dB
SUE antenna gain[7] and noise figure	21 dB and 10 dB
Scheduler and traffic model[6]	Proportional Fair (PF) and full buffer
Type of SBSs	Closed Subscriber Group (CSG) femtocell BSs
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
TTI[8] and scheduler time constant (t_c)	1 ms and 100 ms
Total simulation run time	8 ms

taken from [6]from [7], [7]from [5], [8]from [6].

Performance Evaluation and Comparison (2)

Figure 2(a) shows the path loss response for a SBS with distance *d* of its SUE.

- It can be found that the path loss at distance *d* from a SBS is the most when the SBS operates in the 140 GHz band, and the least, when it operates in the 2 GHz microwave band.
- This implies that to address high capacity and data rate demands of the future mobile networks, the availability of large spectrum bandwidth in the high-frequency bands such as THz bands will play a vital role.

Figure 2(b) shows the response of the average throughput per SUE in different carrier frequencies.

- For LOS signal propagations in the high-frequency bands, the average throughput per SUE decreases with an increase in the carrier frequency. This is because an increase in carrier frequency causes to increase in the distant-dependent path loss as shown in Figure 2(a).
- However, the average throughput per SUE is the lowest when SBSs operate in the 2 GHz low-frequency band. This is due to the NLOS signal propagation that occurs from the presence of large multipath fading components in the low-frequency band.

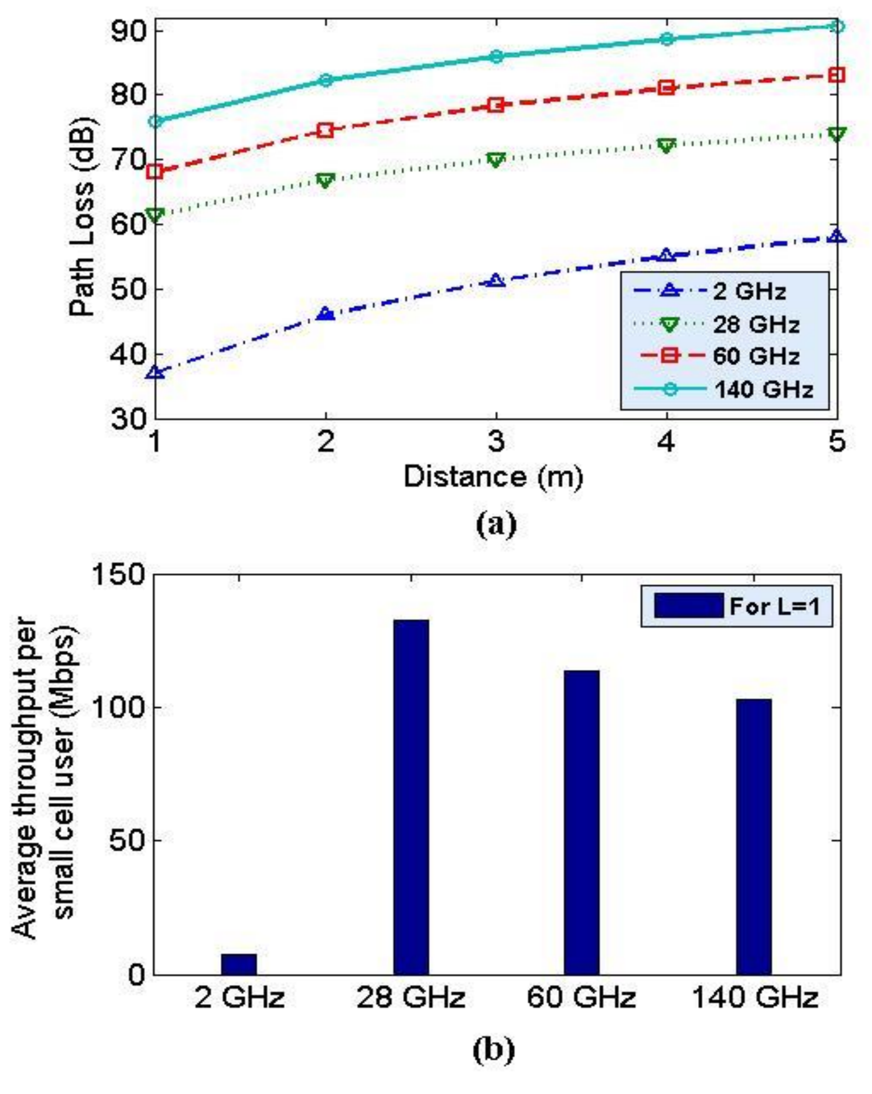

Figure 2. (a) Path loss and (b) average throughput per SUE responses with a variation in the carrier frequency of in-building SBSs.

Performance Evaluation and Comparison (3)

Figures 3(a) and 3(b) show, respectively, the system-level SE and EE performances for the 10 MHz bandwidth of all MUEs.

- From Figure 2(a), since the path loss increases with an **increase in LOS carrier frequency**, the system-level SE and EE improve with a decrease in carrier frequency. Hence, the maximum and minimum improvements in both SE and EE are obtained when SBSs operate in the 28 GHz and 140 GHz bands, respectively.
- However, **due to the NLOS signal propagation** effect, the 2 GHz band provides the worst performance in the average capacity (Figure 2(b)), resulting in realizing the worst system-level SE and EE performances in NLOS 2 GHz carrier frequency as shown in Figures 3(a) and 3(b).

Assume that the **prospective average SE and EE requirements** for 6G mobile networks are, respectively, **10 times** (i.e., 370 bps/Hz) [11] and **10-100 times** (i.e., 0.3µJ/bit - 0.03µJ/bit) [12] higher than that of 5G mobile networks [13]-[14].

- From **Figures 3(a) and 3(b),** it can be found that **all high carrier frequency bands,** i.e., 28 GHz, 60 GHz, and 140 GHz, can achieve both SE and EE requirements expected for 6G mobile networks by reusing spectrum in their respective bands for a reuse factor (i.e., *L*) of 26, 30, and 33, respectively.

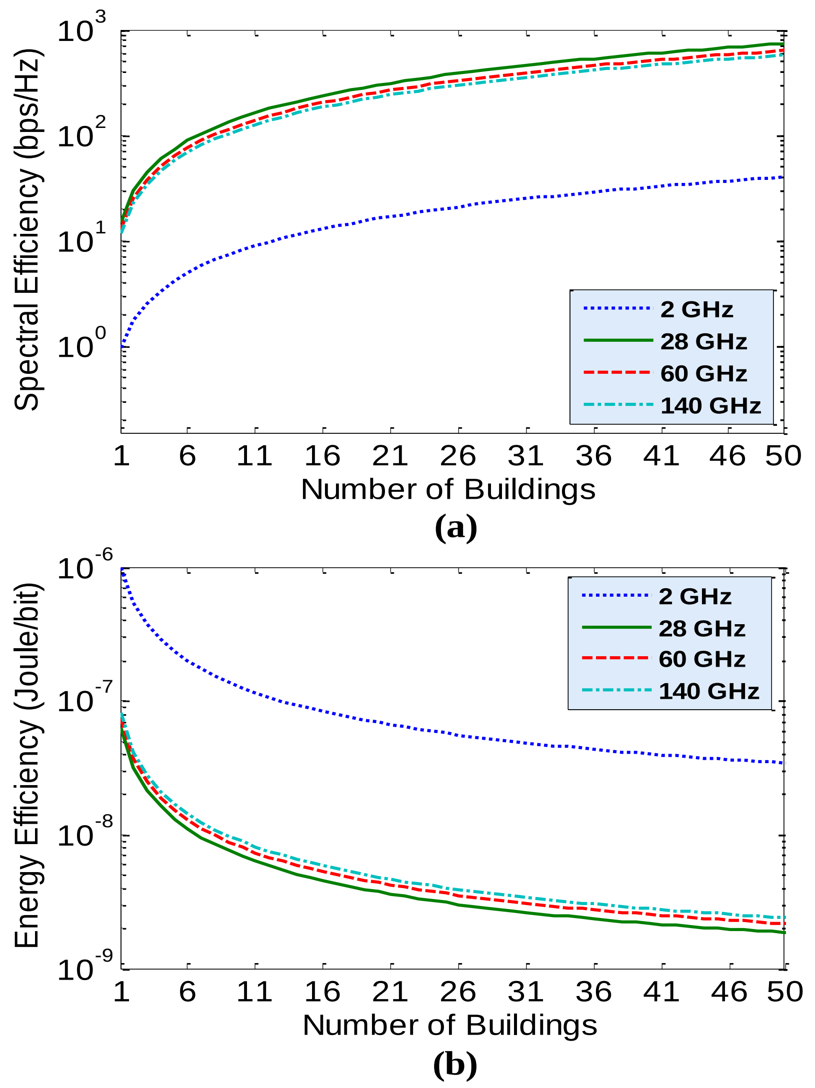

Figure 3. System-level performances with a variation in the carrier frequency of in-building SBSs. (a) spectral efficiency and (b) energy efficiency.

Conclusion

As the signal propagation characteristics vary significantly with a change in carrier frequency, in this paper, we have presented the performance of in-building small cells with the variation of carrier frequency from a low microwave band to a very high Terahertz (THz) band expected for the future Sixth-Generation (6G) mobile networks.

We have derived the average capacity, Spectral Efficiency (SE), Energy Efficiency (EE), and throughput per small cell UE (SUE) and carried out extensive simulation results with a change in carrier frequency from a microwave band (i.e., 2 GHz), through a number of mmWave bands (i.e., 28 GHz and 60 GHz), to a THz band (i.e., 140 GHz).

- It has been shown that due to **the presence of LOS components**, high-frequency signals offer high average capacity and hence SE, as well as average throughput per SUE. Moreover, due to an increase in average capacity, the average energy required per bit transmission is also reduced, resulting in improving EE as well.

- However, due to the **NLOS signal propagation effect**, the 2 GHz band is affected considerably by the multipath fading effect from the reflection, refraction, and scattering phenomenon such that the 2 GHz band provides the worst performance in the average capacity. This results in achieving the worst system-level SE and EE performances.

- Finally, it has been shown that all high carrier frequency bands, i.e., 28 GHz, 60 GHz, and 140 GHz, can achieve both SE and EE requirements expected for 6G mobile networks by reusing spectrum in their respective bands for a reuse factor (i.e., *L*) of 26, 30, and 33, respectively.

References

1. D. López-Pérez, M. Ding, H. Claussen, and A. H. Jafari, "Towards 1 Gbps/UE in Cellular Systems: Understanding Ultra-Dense Small Cell Deployments," IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2078-2101, Fourthquarter 2015, doi: 10.1109/COMST.2015.2439636.
2. A. Chandra, "Comparative Study of 900 MHz and 450 MHz Radio Signals Propagation in an Indoor Environment," Proc. 1996 IEEE International Conference on Personal Wireless Communications Proceedings and Exhibition. Future Access, New Delhi, India, 1996, pp. 247-253, doi: 10.1109/ICPWC.1996.494278.
3. A. M. Al-Samman, et al., "Comparative Study of Indoor Propagation Model Below and Above 6 GHz for 5G Wireless Networks. *Electronics*, vol 8, no. 44, 2019. doi:10.3390/electronics8010044
4. S. Deng, M. K. Samimi, and T. S. Rappaport, '28 GHz and 73 GHz millimeter-wave Indoor Propagation Measurements and Path Loss Models," Proc. 2015 IEEE International Conference on Communication Workshop (ICCW), London, UK, 2015, pp. 1244-1250, doi: 10.1109/ICCW.2015.7247348.
5. N. A. Abbasi, A. Hariharan, A. M. Nair, and A. F. Molisch, "Channel Measurements and Path Loss Modeling for Indoor THz Communication," Proc. 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5, doi: 10.23919/EuCAP48036.2020.9135643.
6. 3GPP. *Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) System Scenarios. Document 3GPP TR 36.942, V.1.2.0, 3rd Generation Partnership Project, Jul. 2007.* [online] Available from: https://portal.3gpp.org/ desktopmodules /Specifications/Specification Details.aspx?specificationId=2592 [retrieved February, 2020]
7. *Simulation Assumptions and Parameters for FDD HeNB RF Requirements. document TSG RAN WG4 (Radio) Meeting #51, R4-092042, 3GPP, May 2009.* [online] Available from: https://www.3gpp.org/ftp/tsg_ran /WG4_Radio/TSGR4_51 /Documents/ [retrieved February, 2020].
8. S. Geng, J. Kivinen, X. Zhao, and P. Vainikainen, "Millimeter-Wave Propagation Channel Characterization for Short-Range Wireless Communications," IEEE Transactions on Vehicular Technology, vol. 58, no. 1, pp. 3-13, Jan. 2009, doi: 10.1109/TVT.2008.924990.
9. G. R. Maccartney, T. S. Rappaport, S. Sun, and S. Deng, "Indoor Office Wideband Millimeter-Wave Propagation Measurements and Channel Models at 28 and 73 GHz for Ultra-Dense 5G Wireless Networks," IEEE Access, vol. 3, pp. 2388-2424, 2015, doi: 10.1109/ACCESS.2015.2486778
10. R. K. Saha, "3D Spatial Reuse of Multi-Millimeter-Wave Spectra by Ultra-Dense In-Building Small Cells for Spectral and Energy Efficiencies of Future 6G Mobile Networks," *Energies, vol. 13, no. 7,* 1748, pp.1-19, 2020. doi: 10.3390/EN13071748
11. Z. Zhang et al., "6G Wireless Networks: Vision, Requirements, Architecture, and Key Technologies," IEEE Vehicular Technology Magazine, vol. 14, no. 3, pp. 28-41, Sept. 2019, doi: 10.1109/MVT.2019.2921208.
12. S. Chen, et al., "Vision, Requirements, and Technology Trend of 6G: How to Tackle the Challenges of System Coverage, Capacity, User Data-Rate and Movement Speed," IEEE Wireless Communications, vol. 27, no. 2, pp. 218-228, April 2020, doi: 10.1109/MWC.001.1900333.
13. C. Wang et al., "Cellular architecture and Key Technologies for 5G Wireless Communication Networks," IEEE Communications Magazine, vol. 52, no. 2, pp. 122-130, February 2014, doi: 10.1109/MCOM.2014.6736752.
14. G. Auer et al., "How much energy is needed to run a wireless network?," IEEE Wireless Communications, vol. 18, no. 5, pp. 40-49, October 2011, doi: 10.1109/MWC.2011.6056691.

End of the Presentation

Thank You …