Coverage Analysis for Indoor-Outdoor Coexistence for Millimetre-Wave Communication

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***Abstract*—Milimeter-wave (mm-wave) communication, which has already been a part of the fifth generation of mobile communication networks (5G), would result in ultra dense small cell deployments due to its limited coverage characteristics. In such an environment, outdoor base stations (BS) will get closer to the buildings, in which users are covered and served by indoor small cells that in turn degrades the user Quality of Experience (QoE) owing to the increased interference caused by the outdoor BSs. In this paper, indoor coverage analysis is conducted by considering a scenario, which includes a multi-storey building and two identical indoor femtocell and outdoor BS operating at 28 GHz. During the simulations, impacts of the outdoor BS's transmit power and distance to the building on the indoor coverage are investigated. In addition, various material types, namely one layer brick, International Telecommunication Union (ITU) 28 GHz concrete, ITU 28 GHz glass, and ITU 28 GHz wood, for the building walls are tested. Results reveal that dielectric properties of the materials are the key factors in determining the severity of the interference caused by the outdoor BS, paving the way for including the effects of material type in network designing and smart city planning.**

***Index Terms*—mm-wave, indoor coverage, 5G, ray tracing, femtocells, smart buildings**

I. Introduction

The fifth generation of mobile communication networks (5G) has been standardized to exploit millimeter-wave (mm-wave) frequencies to provide high data rate connection, seamless connection and robust coverage to both indoor and outdoor users. However, the use of mm-wave comes with new and peculiar challenges, such as limited coverage, since the penetration loss is proportional to the carrier frequency of the electromagnetic signal [1], [2].

As such, providing high data rates to indoor users could be challenging by solely deploying outdoor BSs since the mm-wave signals attenuate greatly depending on the material type and the thickness of the wall [3]. To overcome this issue, deploying local base stations, such as femto BSs inside the building could be an effective solution for delivering high-quality broadband service to indoor users.

Femtocells can share the spectrum with the existing network or work in assigned channels based on the availability of spectrum [4]. In the former case, operating femtocells under the coverage of outdoor BS may degrade the performance of femto users because of the outdoor BS interference inside the building. To satisfy indoor users' demands for a higher quality of service (QoS), received signal-to-interference-plus-noise-ratio (SINR) should be sufficient enough anywhere inside the building. Meanwhile, signal leakage from the femto BS deployed building to outdoor should also be considered and kept minimum otherwise QoS of outdoor users near the building might be affected negatively, because of indoor interference on the outside. Adjusting transmitter power of BSs would be one of the ways of mitigating the impact of mutual interference. However, this method would decrease QoS of users when the transmit power is lessened. Therefore, signal attenuation caused by the propagation through walls and other buildings materials would be the critical parameter to achieve mutual interference reduction. In other words, building walls could play a role as shielding mutual interference between the indoor femto BS and outdoor BS. Since thickness and the type of material used in the building changes wall attenuation in order of 5 dB to 20 dB or more and signal attenuation through doors or windows is around 3 dB [3]. The approach of using buildings as a shielding would help to re-use the same frequencies in the area where small cells are deployed close to each other.

In the literature, a significant number of studies concentrated on the outdoor-to-indoor propagation to increase outdoor coverage to serve indoor users, whereas few research focused on the indoor-to-outdoor case. In [3], a sample floor plan model was built to enable the investigation of interference effect between macro and indoor femto BS. The authors in [5] examined the mutual interference between macro and femto BS, i.e., impacts of the interference caused by femtocell on the users served by macro cell, and the interference caused by macro cell on the users served by femtocell. Although the works in [3], [5] focused on the interference management between indoor and outdoor, both of them are modelled femto and macrocell for particularly 4G networks. The study conducted in [6] analyzed the indoor coverage by deploying a single building scenario with an outdoor deployed BS utilizing high frequencies, e.g., 10, 30, and 60 GHz. However, since the nature of high frequencies, such as mm-waves, are highly susceptible to the penetration loses, covering indoor users with outdoor BS, operating at high-frequencies would not be feasible in terms of user's QoE.

This paper investigates the effects of the interference caused by the outdoor mm-wave BS inside the femtocell deployed

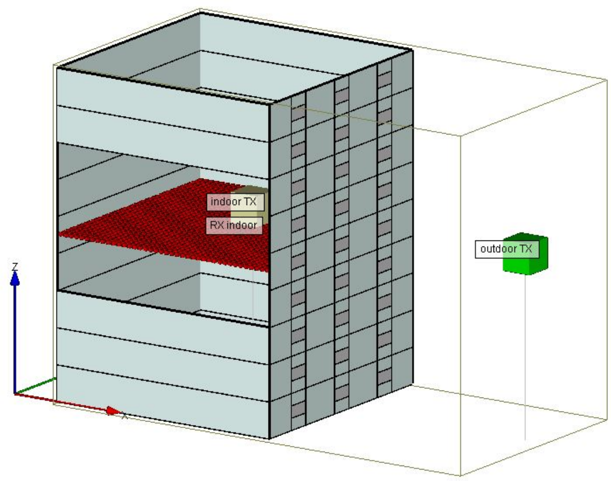

Fig. 1. Simulation environment including a multi-storey building with, indoor and outdoor transmitters, and receiver points inside the building.

building. Of all the factors effecting the interference experienced by indoor users, three integral ones are identified: 1) the transmit power of the outdoor BS; 2) the distance between the outdoor BS and the building of interest; and 3) the material type used for constructing the walls of the building.

The rest of the paper is organized as follows. Section II presents the simulation environment. Section III analyzes the simulation results. Finally, the paper is concluded in Section IV.

II. Methodology

In order to estimate the interference caused by the outdoor BS and to perform an indoor coverage analysis inside a building served by femtocell, a simulation environment is created in Wireless Insite™ software by placing 1600 points of receiver set inside the building, which is neighbour to a mm-wave small cell outdoor BS, as depicted in Fig. 1. In order to observe effects of different material types on the indoor experienced interference, different building scenarios are developed with four different materials used in the walls of the building. In the first scenario, walls are built up using one layer brick. In the following scenarios, walls are changed to frequency-sensitive materials whose dielectric parameters are specified in Wireless Insite™ database, based on the ITU recommendations. In second scenario, ITU 28 GHz concrete is used for the building's walls, while in third scenario walls are changed to ITU 28 GHz wood. The windows in the first, second, and third scenarios are built up by deploying ITU 28 GHz glass with a thickness of 0.003 m. In the last scenario, the full building is created by using ITU 28 GHz glass with a thickness of 0.125 m. Table I shows the dielectric parameters of the materials used in the building. Simulations are conducted for different power values of outdoor small cell BS, such as 0 dBm is selected by considering outdoor BS is in sleep mode, whereas 30 dBm for regular transmitted power for mm-wave BS [7] and 50 dBm in case of outdoor BS which act as backhaul [8] BS introduce interference to inside the building. Furthermore, to account the distance effect on interference due to ultra dense deployment of mm-wave BSs, the distances of 25 m, 50 m and 100 m are selected to illustrate the general trends of how coverage probability alters across the distance range. Table II shows deployment and simulation parameters used in this study.

TABLE I
Dielectric parameters and thickness of the material used in simulated building.

Material type used in the simulated building	Permittivity, ϵ_{r}	Conductivity, σ (S/m)	Thickness, d (m)
Brick (one layer)	4.440	0.0010	0.125
ITU Concrete 28 GHz	5.310	0.4838	0.125
ITU Wood 28 GHz	1.990	0.1672	0.125
ITU Glass 28 GHz (full glass building)	6.270	0.2287	0.125

As shown in the Fig. 1, the source for indoor interference is due to the outdoor BS. Our system model combine two different propagation models, for the case of outdoor mm-wave frequency propagate through the wall we consider through-wall ray propagation model [9] and Friis equation for free space wireless propagation. The combination of these model can be expressed as

$$\begin{aligned}P_r(\mathrm{dBm}) =& P_t(\mathrm{dBm}) + \sum_{i\in antenna} G_i(\mathrm{dB}) + 20\log_{10} T \\ & - 20\log_{10} f(\mathrm{MHz}) - 20\log_{10} d(\mathrm{m}) + 27.6,\end{aligned} \tag{1}$$

where P_r and P_t are the received and transmit power, respectively; G_i represents all the gains associated with antenna and channel link; d is the distance between receiver node and transmitting antenna; f is the frequency of communication; T is the gain affiliated with Fresnel reflection and transmission coefficient [9] during propagation of mm-wave. Reflection coefficients which depend on material permittivity and the polarization, play important role in our system model which based on ray tracing simulations. Reflection coefficients for perpendicular ($|\Gamma_\perp|$) and parallel ($|\Gamma_\parallel|$) polarizations are given as

$$|\Gamma_\perp| = \frac{\sin(\beta) - \sqrt{\varepsilon_{\mathrm{r}} - \cos^2(\beta)}}{\sin(\beta) + \sqrt{\varepsilon_{\mathrm{r}} - \cos^2(\beta)}}, \tag{2a}$$

$$|\Gamma_\parallel| = \frac{-\varepsilon_{\mathrm{r}}\sin(\beta) + \sqrt{\varepsilon_{\mathrm{r}} - \cos^2(\beta)}}{\varepsilon_{\mathrm{r}}\sin(\beta) + \sqrt{\varepsilon_{\mathrm{r}} - \cos^2(\beta)}} \tag{2b}$$

where ε_{r} is the material permittivity of the reflecting surface and β is the angle between the incident ray and the reflected surface [10].

III. Simulation Results

The results based on simulations performed in Wireless Insite™ X3D model, which is suitable for indoor or outdoor scenes by providing high fidelity, GPU accelerated, 3D ray

TABLE II
SIMULATIONS AND DEPLOYMENT PARAMETERS.

Simulations Parameters	Parameter Value
Carrier frequency (GHz)	28
Number of buildings	1
Building size (m)	20x20x27
Number of floors	9
Number of outdoor base stations	1
Number of indoor base stations (femtocells)	1
Distance between outdoor BS and the building (m)	{25, 50, 100}
Bandwidth (MHz)	100
Outdoor BS height (m)	15
Indoor BS height (m)	15
Indoor receiver height (m)	13.5
Number of indoor receiver points	1600
Indoor transmit power (dBm)	30
Outdoor transmit powers (dBm)	{0, 30, 50}
Antenna type (indoor/outdoor)	Half-wave dipole

tracing as well as accounting atmospheric attenuation, effect of the reflection and transmission on mm-wave frequency.

The effects of materials are analyzed by incorporating the coverage probability of the signal in the area of interest. The coverage probability is defined as the probability that the SINR received by the arbitrary user exceeds a certain SINR threshold $\bar{\gamma}$. Mathematically the coverage probability is given by

$$\mathcal{P}_c = \mathbb{P}\left\{ \frac{P_{r(in)}}{\sum_{i\epsilon \setminus BS_{in}} P_{r(out)} + \sigma^2} = \bar{\gamma} > \gamma_{\text{th}} \right\}, \tag{3}$$

where any other indoor BS, denoted as BS_{in}, is removed from the interfering serving indoor BS because of small contribution to the interference, we assume frequency reuse for indoor BS. $\mathcal{P}_c$ is the coverage probability; $P_{r(in)}$ and $P_{r(out)}$ are received power from indoor and outdoor BSs respectively; σ^2 is the noise; $\bar{\gamma}$ is the experience SINR for any arbitrary receiver, and γ_{th} is the set threshold SINR.

We first study the effect on the varying power on the same distance for different materials. Fig. 2 and Fig. 3 show coverage probability for four different materials, brick & ITU 28 GHz concrete and ITU 28 GHz glass & ITU 28 GHz wood with variable outdoor transmitting power at 25 m, respectively.

When the transmitter power is 50 dBm, it can be seen that brick has a high transmission gain for mm-wave frequencies comparing with other materials. The trend shows even at lower transmit power, brick demonstrates the same behaviour of higher negative slope as it can be seen in ITU 28 GHz glass. When the distance is changed to 50 m as shown in Fig. 4 and Fig. 5, coverage probability for brick increases noticeably while coverage probability of other materials increase slightly compared to when the distance is 25 m.

Figs. 6 and 7 illustrate simulation results when distance is 100m, where brick has a higher coverage probability even with the higher outdoor transmit power, however its coverage probability remains lower with respect to other materials.

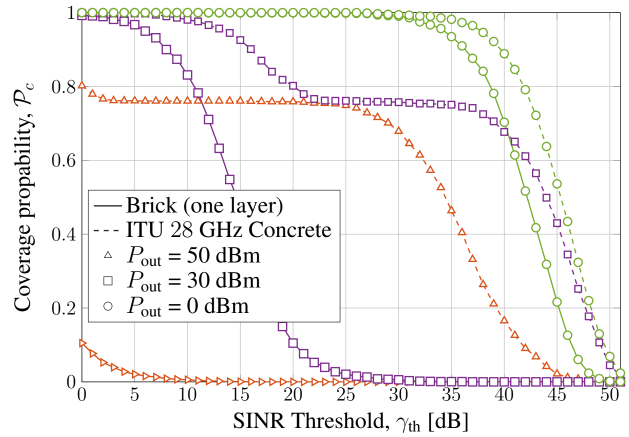

Fig. 2. Coverage probability vs. SINR threshold for brick and concrete for different TX Power at 25 meter.

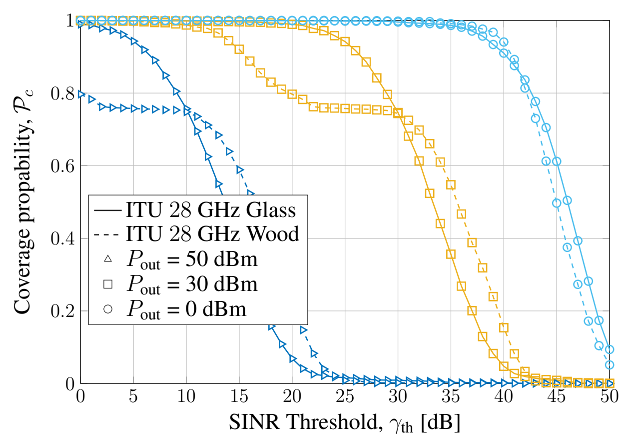

Fig. 3. Coverage probability vs. SINR threshold for glass and wood for different TX Power at 25 meter.

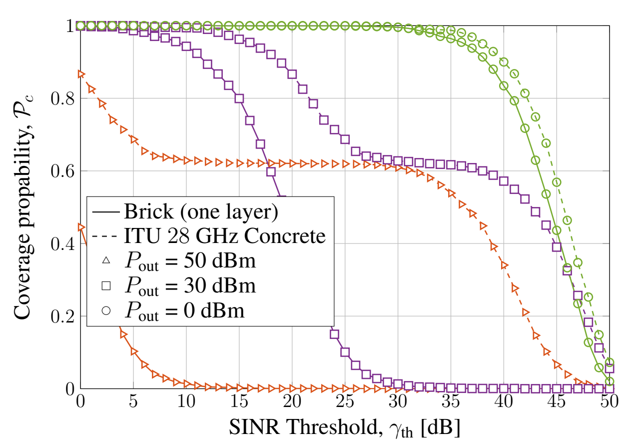

Fig. 4. Coverage probability vs. SINR threshold for brick and concrete for different TX Power at 50 meter.

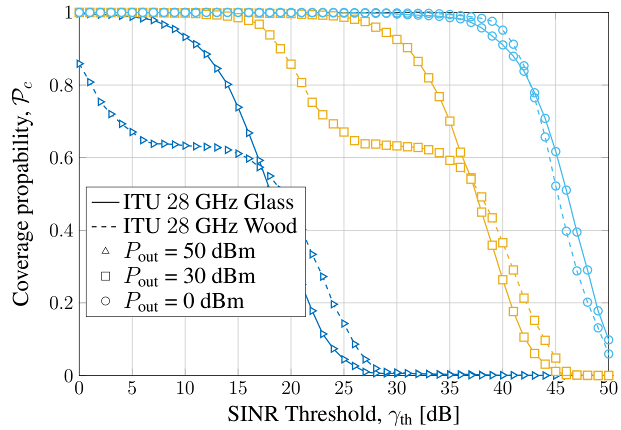

Fig. 5. Coverage probability vs. SINR threshold for glass and wood for different TX Power at 50 meter.

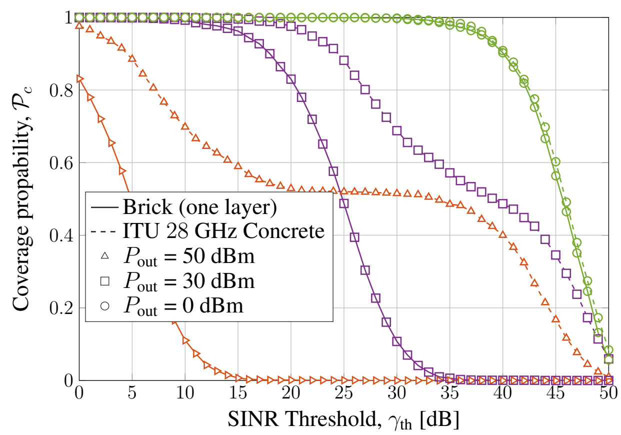

Fig. 6. Coverage probability vs. SINR threshold for brick and concrete for different TX Power at 100 meter.

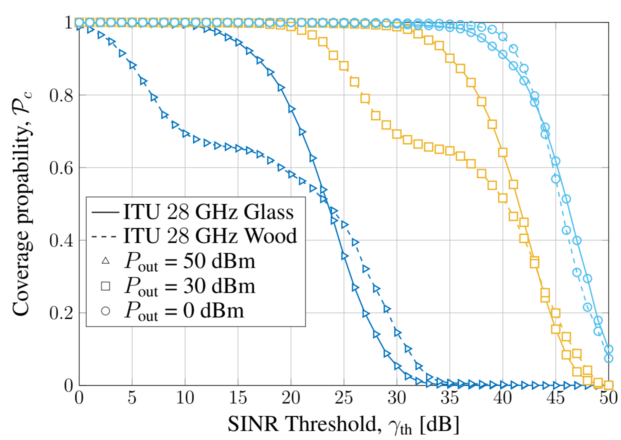

Fig. 7. Coverage probability vs. SINR threshold for glass and wood for different TX Power at 100 meter.

Overall, it can be seen that coverage probability of concrete is higher than the brick at different distances while outdoor transmit power is changed. For environment which is highly populated with outdoor mm-wave BSs, utilizing frequency dependant concrete would benefit indoor users by blocking the outdoor signal. In comparison between ITU 28 GHz glass and ITU 28 GHz wood, the coverage probability for both materials look quite similar for higher SINR threshold; however, the difference in coverage probability become particularly noticeable for lower SINR threshold in all power and all distances. Nonlinearity behaviour shown between the materials attributed by the fact that the building is non-homogeneous structure and through out the simulation the building is comprised of glass windows.

IV. Conclusion

This paper analyses the outdoor BS interference effect inside the building when the different type of materials used in the walls of building. We developed a single building model and analyze the coverage probability and effects of varying outdoor BS transmit power with the fixed indoor BS transmit power. The results reveal the importance of choosing the material type when outdoor BS is close to the building. Moreover, the outdoor BS interference effect should be minimized, when the frequency re-use technique is deployed in very short insite distances. As a future work, we plan to extend our study by researching the outdoor BS polarization effect on interference.

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References

[1] N. Al-Falahy and O. Y. Alani, "Millimetre wave frequency band as a candidate spectrum for 5G network architecture: A survey," *Physical Communication*, vol. 32, pp. 120–144, feb 2019.

[2] M. M. Molu, P. Xiao, M. Khalily, K. Cumanan, L. Zhang, and R. Tafazolli, "Low-complexity and robust hybrid beamforming design for multi-antenna communication systems," *IEEE Transactions on Wireless Communications*, vol. 17, no. 3, pp. 1445–1459, March 2018.

[3] M. Mirahmadi, A. Shami, and A. Al-Dweik, "A building architecture model for predicting femtocell interference in next-generation networks," in *2012 IEEE International Conference on Communications (ICC)*, June 2012, pp. 5059–5063.

[4] 3GPP, "3G; Home NodeB Study Item Technical Report," 3rd Generation Partnership Project (3GPP), TS 38.913 , Sept. 2008.

[5] A. Alexiou, C. Bouras, V. Kokkinos, K. Kontodimas, and A. Papazois, "Interference behavior of integrated femto and macrocell environments," in *2011 IFIP Wireless Days (WD)*, Oct 2011, pp. 1–5.

[6] E. Semaan, F. Harrysson, A. FuruskÃď'r, and H. Asplund, "Outdoor-to-indoor coverage in high frequency bands," in *2014 IEEE Globecom Workshops (GC Wkshps)*, Dec 2014, pp. 393–398.

[7] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[8] M. E. Leinonen, G. Destino, O. Kursu, M. Sonkki, and A. Pärssinen, "28 GHz wireless backhaul transceiver characterization and radio link budget," *ETRI Journal*, vol. 40, no. 1, pp. 89–100, 2018.

[9] D. Pena, R. Feick, H. D. Hristov, and W. Grote, "Measurement and modeling of propagation losses in brick and concrete walls for the 900-MHz band," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 1, pp. 31–39, Jan 2003.

[10] M. U. Sheikh, K. Hiltunen, and J. Lempiainen, "Enhanced Outdoor to Indoor Propagation Models and Impact of Different Ray Tracing Approaches at Higher Frequencies," *Advances in Science, Technology and Engineering Systems Journal*, vol. 3, no. 2, pp. 58–68, 2018.