Employing 60 GHz ISM Band for 5G Wireless Communications

(Invited Paper)

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***Abstract*—Wireless data traffic is continuously increasing due to the steady rise in both connected device number and traffic per device. Wireless networks, traditionally confined below 6 gigahertz, are getting clogged and unable to satisfy the ever-increasing demands of its users. Already aware of this, telecommunications industry and academia have been working on solutions. One of the main methods for throughput increase is operation bandwidth expansion; however, sufficient spectrum is not available within the conventional frequencies. Following various considerations, 60 GHz industrial, scientific and medical radio band has been selected as the new spectrum to be utilized and wireless personal and local area network standards for the band are already completed. In line with the stated developments, this paper proposes the use of 60 GHz band for the fifth generation (5G) communication systems. After very briefly setting the scene of the current wireless communication networks, the physical layer properties of the 60 GHz band are presented. A representative indoor simulation between the fourth generation and proposed 5G cases is set and performed. The results are assessed and compared before concluding the paper.**

***Index Terms*—Future wireless communication, 5G mobile communication, millimetre wave communication, IEEE standards.**

I. Introduction

The increase in requirement of information and data within our daily lives and routines has been a major driver for connectivity growth for more than a decade now. Up until the end of the third generation (3G) mobile telecommunication systems, it can be argued that telecommunication and data services have been treated as separate features. However, with the introduction of fourth generation (4G), network convergence took over and all services essentially became a form of data communications.

Conventional mobile and data communications have always been conducted within the frequency bands below 6 gigahertz (GHz). The simple reasons are the favourable electromagnetic (EM) wave propagation conditions and hardware capabilities. However, as the demand for communications exponentially increased the available spectrum became insufficient. Wireless local area networks (WLANs) operate within the industrial, scientific and medical (ISM) radio bands centred at 2.45 and 5.8 GHz [1], the latter being extended through 5150 - 5350 megahertz (MHz) and 5470 - 5725 MHz with further restrictions [2]. However, because IEEE 802.11 initially designed for best service support through contention-based access and due to the open nature of the spectrum, despite the quality of service (QoS) amendments like IEEE 802.11e [3], service guarantee is not possible. To offer reliable and satisfactory communications, exclusive spectrum is needed, and therefore the high-priced mobile spectrum auctions occur. To get an idea of the worth of bandwidth, the July 2012 dated technical report commissioned by the United Kingdom (UK)'s Office of Communications can be consulted [4]. One part of the report presents benchmark valuation results which are compiled using similar recent auctions held across the Europe. For larger incumbent operators the value of the spectrum in the 800 MHz band is found to be between £0.460 and £0.714 per MHz per capita. This amount decreases to the £0.087 - £0.121 range for the 2.6 GHz band. 800 MHz is important for widespread coverage, whereas 2.6 GHz is necessary to support high data rates, and the nearly 6 times valuation difference between the bands therefore stems from the respective economic importance of the stated channel properties. The monetary quantities given in the report further validated by the results of UK's 4G mobile auction, which was held in February 2013 [5].

Providing data communications without facing the hefty upfront licence costs requires resorting to the ISM bands. The corresponding designations according to the International Telecommunication Union (ITU) Radiocommunication Sector (ITU-R)'s Radio Regulations, Edition of 2012 [1], are provided in Table I. Since the 2.4 and 5 GHz ISM bands are already being utilized by WLANs, in order to satisfy the data rate requirements of the next-generation of wireless communication systems, ISM bands in the higher frequencies should be put into use. 24 and 61 GHz bands are the next ones in line. While 24 GHz have better EM wave propagation characteristics due to lower atmospheric and free-space losses, it is confined within a bandwidth of 250 MHz. On the contrary, although the 500 MHz wide 61 GHz ISM band is not large

TABLE I
ITU-R DESIGNATED ISM BANDS

Frequency Range			Bandwidth	
6.765	6.795	MHz	30	kHz
13.553	13.567		14	
26.957	27.283		326	
40.66	40.70		40	
433.05	434.79		1.74	MHz
902	928		26	
2.4	2.5	GHz	100	
5.725	5.875		150	
24	24.25		250	
61	61.5		500	
122	123		1	GHz
244	246		2	

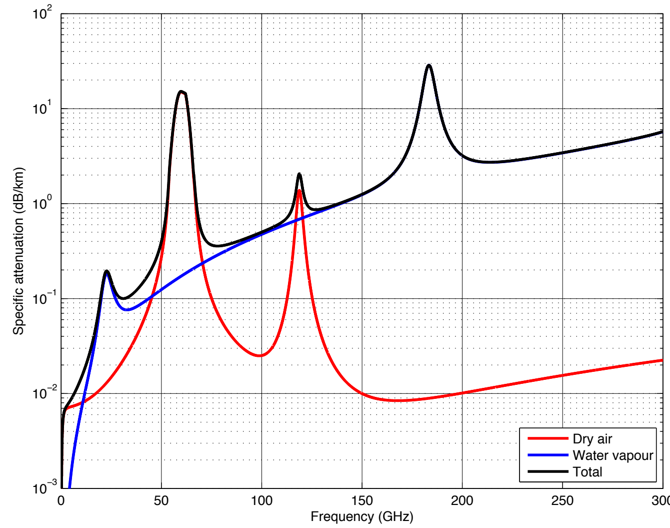


Fig. 1. Specific attenuation due to atmospheric gases, calculated under standard atmospheric conditions and up to 300 GHz at 1 MHz intervals.

by itself, because the whole or continuous parts of the 57 - 66 GHz frequency band surrounding it has been allocated for unlicensed operations in all of the major regulatory domains, the 60 GHz presents a unique realizable opportunity for worldwide very high data rate supporting WLANs.

In consideration of the stated arguments, this paper proposes the utilization of the 60 GHz ISM band for 5G communication systems and presents an indoor coverage simulation to compare transmission properties between a channel standardized within the 60 GHz band and the highest allocated frequency band for 4G systems, which is 3.5 GHz. With this aim Section II provides an overview on the EM propagation characteristics of the 60 GHz ISM band. The performed simulations are explained in detail in Section III whereas the results together with their explanations are available in Section IV, which is then followed by the conclusion.

II. The 60 Gigahertz Band

The unmatched 9 GHz of unlicensed spectrum makes many data-intensive applications viable, however this comes at the cost of very poor EM wave propagation properties. While intensive signal degradation is useful for some specific attributes like frequency reuse, it primarily reduces the signal-to-noise ratio (SNR), thus decreasing the coverage and link quality. In Fig.1 the specific attenuation up to 300 GHz due to dry air and water vapour under standard atmospheric conditions of 15 °C, 1013 hPa and 7.5 g/m^3 water vapour density, and calculated according to the Recommendation ITU-R P.676-9 [6], is illustrated. When the figure is examined the four local maxima are seen to be occurring at 22.748 GHz with 0.196 dB/km, 59.755 GHz with 15.225 dB/km, 118.788 GHz with 2.065 dB/km and 183.376 GHz with 28.7 dB/km. Comparing these frequencies with the assigned ISM bands in Table I, it can be concluded that actually the bands with the locally worst transmission characteristics, thus having little or no economic value, are released for open use.

In Fig.2 emphasis is given on the specific attenuation until the local minimum of 78.002 GHz. Additionally included in the figure are the attenuations due to rain for rates of 4, 16 and 25 mm/h, representing moderate, heavy and very heavy rain categories, respectively. Recommendation ITU-R P.838-3 [7] provides the procedure to calculate the specific attenuation due to rain for frequencies up to 1 THz and in the figure vertical polarization is assumed. According to the recommendation, general behaviour of rain attenuation between 1 and 1000 GHz can be described as a decelerating curve that almost flatlines around and after 100 GHz.

When the properties of EM wave propagation in 60 GHz is compared with the 2.4 and 5 GHz bands, the main difference is seen to be the additional free-space losses of 27.96 and 21.58 dB, respectively, for the same transmission distances. At 60 GHz attenuation by atmospheric gases is nearly 15.17 dB/km whereas this is virtually non-existent for the 2.4 and 5 GHz bands. In-building material absorption is also larger at 60 GHz [8]–[10]. When all these greater losses for 60 GHz are combined it can be inferred that multipath contributions would be limited and highly directive antennas are necessary to maintain reliable communication links.

One of the main steps towards standardization of a new frequency band is channel modelling, and as two 60 GHz wireless personal area network (WPAN) standards, ECMA-387 [11] and IEEE 802.15.3c [12], are available since December 2008 and October 2009, respectively, together with the only WLAN standard for 60 GHz, IEEE 802.11ad [13], which is ratified in December 2012, propagation studies are comparatively advanced. Presently the IEEE 802.11ad channel model [14] is commonly used as the benchmark for comparison by newly proposed models. The model adopts ray clustering and defines two sets of parameters for intercluster and intracluster characteristics, together with extension for polarization impact support. The intercluster parameters consist of amplitude, time of arrival and azimuth and elevation angles of arrival and departure, whereas intracluster parameters model a central ray with fixed amplitude surrounded by precursor and postcursor rays, and therefore contains the number of rays and rays'

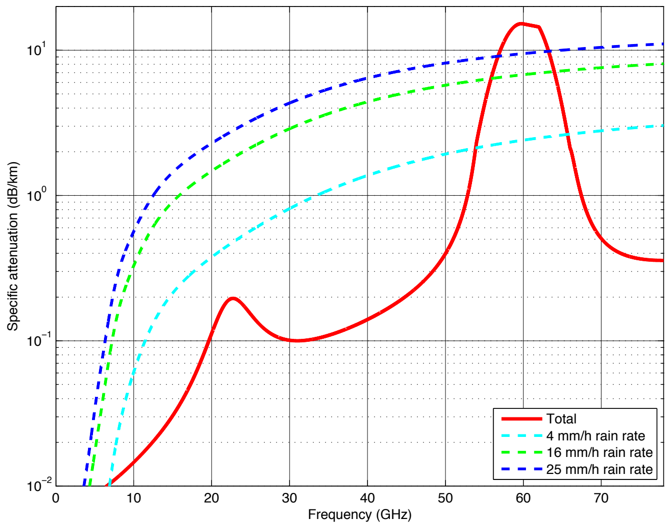


Fig. 2. Specific attenuation due to atmospheric gases and rain, calculated up to 78.002 GHz and for rain rates of 4, 16 and 25 mm/h.

K-factors, power decay times, arrival rates and amplitude distributions.

III. Indoor Simulations

Low-cost millimetre wave (mm-wave) device technologies based on silicon and complementary metaloxidesemiconductor are recently surging with output powers of different implementations are yet to reach adequate levels. Moreover, since the primarily envisioned benefit of 60 GHz utilization is expected to be extremely high peak data rates that are comparable to the current wired communication standards, it is appropriate to compare current 4G systems with proposed mm-wave 5G system in a deployment scenario where data rate maximization is intended. Correspondingly, out of the four test environments defined in report ITU-R M.2135-1 [15], indoor test environment with indoor hotspot deployment scenario matches the assessment purposes.

The scenario, as described in the said report and based essentially on [16], contains one floor of a building with 16 rooms, which are divided equally between each side of the corridor that is 120 m × 20 m. The rooms are 15 m × 15 m apiece and the height of the floor is 6 m. Two base stations (BSs) are planned for the scenario, placed in the middle of the corridor and 30 metres away from the ends of the floor. In line with this plan, for the simulation, authors' laboratory and the part of the hall directly in front of the room is selected as a real world example. Only one room is selected because at 60 GHz in-building material absorptions together with attenuation due to atmospheric gases are high enough to severely limit the coverage of a mm-wave band BS, thus also constraining the access network architecture accordingly. Furthermore, the choice of the limited part of the hall included in simulations is due to the room-corridor measurement results provided in [16]: Additional walls to be propagated beyond the front of the room cause a leap in path loss (PL).

The authors' laboratory has dimensions of 12.12 m × 11.64 m × 3.26 m. It is separated from the hall with a 0.2 m thick wall that is constructed of sand-lime brick having a 1.82 m wide high-density fibreboard (HDF) door and the hall is 2.8 metres across. For the simulations one BS, located exactly on the centre point of the ceiling, is presumed. 4G simulation is shaped according to the baseline configuration parameters provided in [15] for the indoor hotspot scenario: Total transmit power of the BS is assumed to be 24 dBm with no antenna gains anticipated at either BS or user equipment (UE), and noise figures for the BS and UE are taken to be 5 and 7 dB, respectively. Bandwidth is taken on the large side with 100 MHz and carrier frequency is selected as 3.5 GHz, which is the midpoint of the highest allocated frequency band for mobile services, 3400 - 3600 MHz, by ITU's Radio Regulations, Edition of 2012. Temperature is assumed to be 15 °C for the noise power spectral density calculations and system margin is accepted to be 10 dB. Signal-to-noise ratio (SNR) is calculated for comparison in both simulations and for the 4G case respective line-of-sight (LOS) and non-line-of-sight (NLOS) PL models from [15] are employed, which, with d being distance in meters and f_c being carrier frequency in GHz, are:

$$\mathrm{PL_{LOS}} = 16.9\log(d) + 32.8 + 20\log(f_c), \tag{1}$$

$$\mathrm{PL_{NLOS}} = 43.3\log(d) + 11.5 + 20\log(f_c). \tag{2}$$

5G mm-wave simulation parameters, on the other hand, are constrained by the available literature on the subject. One useful document is the channel models that are developed for the IEEE 802.11ad standardization process [14] and the LOS PL model of the conference room STA-AP sub-scenario, which is provided below, is used for the simulations:

$$\mathrm{PL_{LOS}} = 20\log(d) + 32.5 + 20\log(f_c). \tag{3}$$

In line with the operating classes defined in IEEE 802.11ad, the first channel set which starts at 57.24 GHz is selected for the 5G simulations, together with the common bandwidth of 2160 MHz. Unlike 4G case, since official guidelines are not available for mm-wave simulations, for the sake of accuracy power parameters are selected from the mm-wave transmitters (TXs) which are currently available for purchase. One such TX is Hittite Microwave Corporation's model HMC6000LP711E [17], which has 16 dBm transmit power and 7.5 dBi antenna gain, and these values are used in simulations with antenna gain assumed at both TX and receiver ends. For comparison objectivity noise figures are not changed, however system margin is assumed to be 5 dB since antenna directivity reduces the likelihood of unanticipated events. To detect the hall power levels, ray tracing approach is appended to (3). According to Lambert-Beer's attenuation law, the intensity of a beam propagating through an absorbing medium can be expressed with

$$I_2 = I_1 \exp\left(-\int_{P_1}^{P_2} \alpha(\mathbf{r})\mathrm{d}l\right), \tag{4}$$

TABLE II
SIMULATION PARAMETERS

Quantity	4G		5G
Transmitting power	24	dBm	16
TX antenna gain	0	dBi	7.5
RX antenna gain	0		7.5
Carrier frequency	3.5	GHz	58.32
Noise bandwidth	0.1		2.16
BS noise figure	5	dB	5
UE noise figure	7		7
System margin	10		5

where the absorption coefficient α varies along the position vector $\mathbf{r}$, which is extended over a distance of l between the points P_1 and P_2. For the simulations the absorption coefficient is assumed to be constant, reducing (4) to

$$I_2 = I_1 \mathrm{e}^{-\alpha l}. \tag{5}$$

Since comprehensive mm-wave characterization of building materials are not currently available in literature and considering the fact that absorption coefficients of brick and wood does not tend to alter much below 100 GHz [9], the absorption coefficients available for 100 GHz, which are 171 and 185 m^{-1} for sand-lime brick and HDF [10], respectively, are used for the simulations. A summary of the simulation parameters is provided in Table II.

IV. Performance Evaluation

The simulations are run for each 1 cm^3 volume within the defined laboratory and hall area, and results are provided for two different heights: 0.75 m, representing the average height of a desk within an office room and covering fixed communications, and 1.75 m, representing the ear level of a standing person and covering mobile communications.

A. Received Power

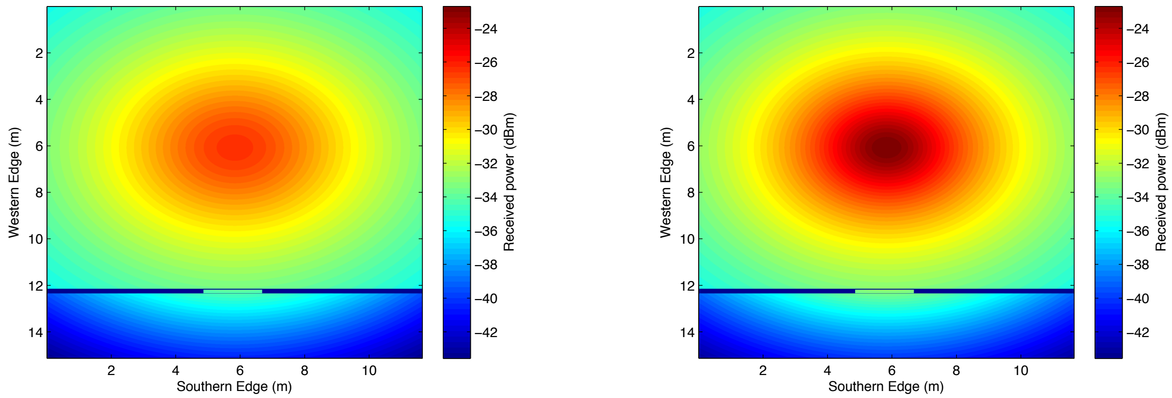
In Fig.3 received power outcomes of 4G simulation are provided for both heights, using the same colour scale. For visualization purposes received power inside the wall and door is matched to the lowest power level within the respective planes for all the figures in this section, thus the wall and door indent are clearly visible in Fig.3. As expected, the power levels gradually decrease as the distance to the BS increases, and since Fig.3b is closer to the BS, the power levels are higher for the $h = 1.75$ m case.

5G simulation results for power outcomes are presented in Fig.4. For better illustration different colour scales are used between the figures. When Fig.4a is reviewed in detail, firstly a power difference of nearly 20 dB can be noticed for the laboratory area between the 4G and 5G cases. The maximum received power is -44.81 dBm for 5G simulation and the power drop is in line with the additional free-space loss for 60 GHz which is explained in Section II. The second consideration is the very high power difference between the extremes of the result. The minimum received power stands at -269.22 dBm, setting the power difference on the order of the immensely high 220 dB, and the absorption through the wall is the main reason for this. Although exact ray tracing with true refraction angles is conducted for simulations, to provide a general idea on the effect of material absorption, according to (5), propagation through 20 cm of sand-lime brick causes a loss of 148.53 dB, whereas 4 cm thick HDF door reduces the power by 32.14 dB. These facts clearly demonstrate the coverage boundaries for the 60 GHz communication systems: Unless the rooms are parted with thin materials having low absorption coefficients, the coverage is confined within one room and a different BS or access point is required for each room which is to be included in the network. Third aspect to contemplate is the trapezoid shape occurring behind the door. The reason is, rays passing through the top of the door form a much wider horizontal angle compared to the ones directly hitting the door on the $h = 0.75$ m plane, and so spread over a longer line.

To demonstrate power distribution better, in Fig.4b wall propagated hall area is left out, and the colour scale is set between the maximum received power of -40.4 dBm and -90 dBm, where the minimum of the remaining of the 1.75 m plane is nearly -89 dBm. Tighter colour scale makes the nearly 35 dB loss caused due to absorption by the door easier to notice. One other difference between the received power results of 5G simulations is the smaller trapezoid area on the $h = 1.75$ m plane. Although the hall is 2.8 m across, since the door is only 2.09 m long, rays originated from the BS that is 6.06 m away on horizontal axis and passing through the 0.36 m segment of the door are unable to cover the entire hall.

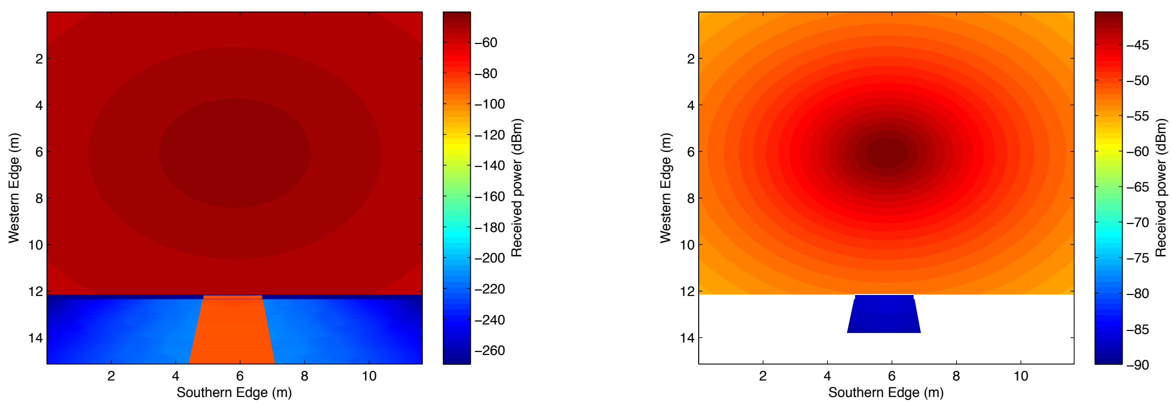
B. Signal-to-Noise Ratio

Remaining figures compare the SNR values between the 4G and 5G simulations. Fig.5a shows the calculated SNR values for the $h = 0.75$ m plane of the 4G case. As can be seen from the plot, values range from 30 to 50 dB, which are much higher than the 14.9 dB required for successful transmission with 16-ary quadrature amplitude modulation (16-QAM) and bit error ratio (BER) of 10^{-6}. Here 16-QAM is chosen as the performance parameter since it is the highest defined modulation technique in the latest completed 3GPP specification, Release 11. The outcome for 4G is as expected since it is an accomplished technology with known end results. Fig.5b, on the other hand, presents the SNR values of 5G simulation. Maximum SNR achieved is 18.85 dB, which is safely higher than the successful quadrature phase-shift keying (QPSK) modulated transmission with 10^{-6} BER limit of 10.78 dB. Although modulation techniques as high as 64-QAM are defined within the IEEE 802.11ad standard, since at 60 GHz QPSK is capable of providing a maximum data rate of 2079 Mb/s, for initial 60 GHz deployments QPSK performance can be accepted as satisfactory. However, SNR on the furthest point of the room within the 0.75 m plane drops to 8 dB. This clearly shows the necessity of high gain antennas and output power transmitters, even for in-room communications. With the wall propagated hall area again left out, SNR in



(a) $h = 0.75$ m (b) $h = 1.75$ m

Fig. 3. Received power outcomes of 4G indoor hotspot deployment simulation, displayed for two different heights.



(a) $h = 0.75$ m (b) $h = 1.75$ m

Fig. 4. Received power outcomes of 5G mm-wave simulation, displayed for two different heights.

the corridor ranges between -22.7 and -29.5 dB, the latter of which also is the end of the colour scale. As reliable communication is not possible at these rates, for practical use of 60 GHz band, alternative solutions, such as dual frequency operation with a lower band or constructing new buildings with wireless communications infrastructure just like water or energy infrastructures, should be employed.

Finally, Fig.6 illustrates the SNR values for the $h = 1.75$ m plane. Apart from slightly higher values due to being closer to the BS, there is not any observable difference between Fig.5 and 6.

V. Conclusion

In this paper utilization of 60 GHz ISM band for the forthcoming 5G wireless communication systems is explored. Following a broad assessment on the current wireless and mobile communication networks, physical layer properties of 60 GHz band is explained. A realistic indoor simulation along the lines of ITU-R guidelines and commercial off-the-shelf circuitry is set for comparing present 4G and proposed 60 GHz 5G systems. From the results the suitability of 60 GHz for in-room communications can be deduced. However, the need for a novel indoor access network architecture to establish an uninterrupted communications link in 60 GHz band is also apparent.

Acknowledgement

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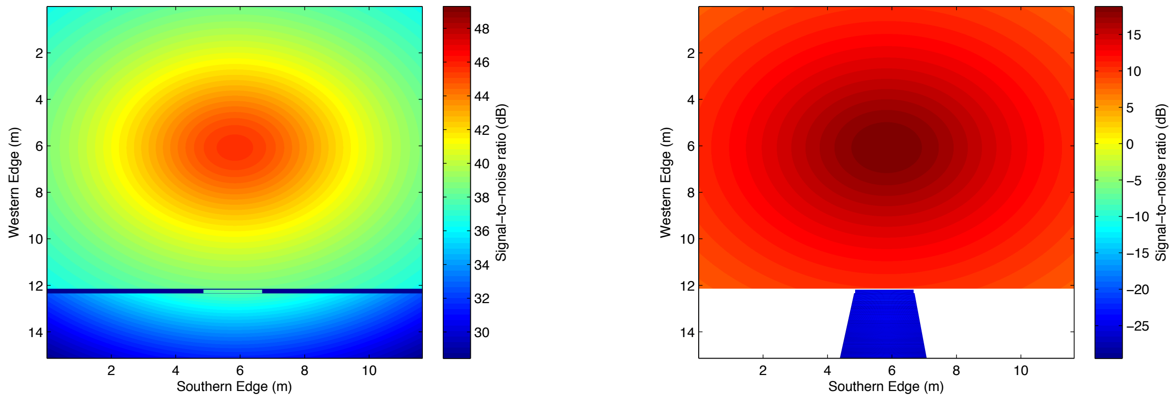
References

[1] "The Radio Regulations, Edition of 2012," 2012.

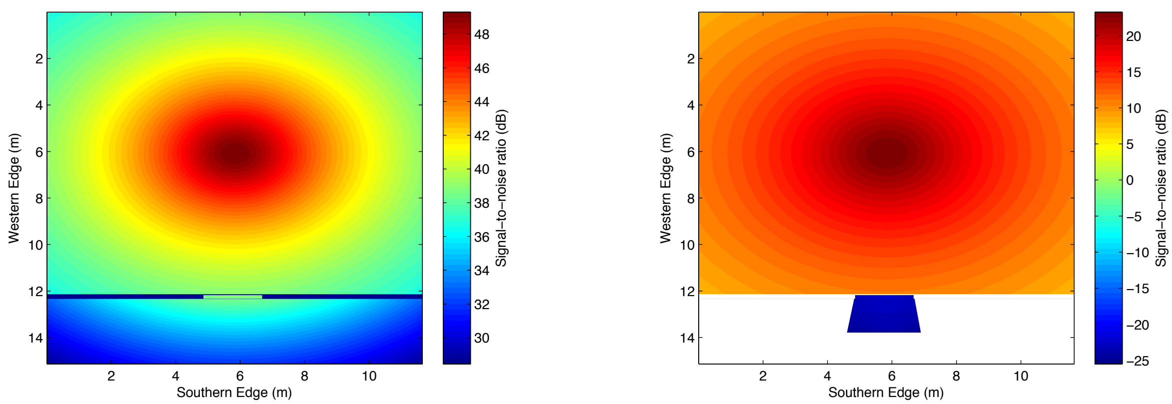
[2] "Resolution ITU-R 229: Use of the bands 5 150-5 250 MHz, 5 250-5 350 MHz and 5 470-5 725 MHz by the mobile service for the implementation of wireless access systems including radio local area networks," *ITU-R Resolutions, ITU, Geneva, Switzerland*, 2012.

[3] "IEEE Standard for Information technology–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 8: Medium Access Control (MAC) Quality of Service Enhancements," *IEEE Std 802.11e-2005 (Amendment to IEEE Std 802.11, 1999 Edition (Reaff 2003)*, pp. 1–212, 2005.



(a) 4G simulation (b) 5G simulation

Fig. 5. SNR outcomes at $h = 0.75$ m, displayed for both simulations.



(a) 4G simulation (b) 5G simulation

Fig. 6. SNR outcomes at $h = 1.75$ m, displayed for both simulations.

[4] DotEcon Ltd. and Aetha Consulting Ltd., "Spectrum value of 800MHz, 1800MHz and 2.6GHz," Tech. Rep., 2012.

[5] Ofcom, "Ofcom announces winners of the 4G mobile auction," 2013.

[6] "Recommendation ITU-R P.676-9: Attenuation by atmospheric gases," *ITU-R Recommendations, P Series Fasicle, ITU, Geneva, Switzerland*, 2012.

[7] "Recommendation ITU-R P.838-3: Specific attenuation model for rain for use in prediction methods," *ITU-R Recommendations, P Series Fasicle, ITU, Geneva, Switzerland*, 2005.

[8] B. Langen, G. Lober, and W. Herzig, "Reflection and transmission behaviour of building materials at 60 GHz," in *Personal, Indoor and Mobile Radio Communications, 1994. Wireless Networks - Catching the Mobile Future., 5th IEEE International Symposium on*, pp. 505–509 vol.2.

[9] R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koch, and T. Kurner, "Terahertz characterisation of building materials," *Electronics Letters*, vol. 41, no. 18, pp. 1002–1004, 2005.

[10] R. Piesiewicz, C. Jansen, S. Wietzke, D. Mittleman, M. Koch, and T. Kurner, "Properties of Building and Plastic Materials in the THz Range," *International Journal of Infrared and Millimeter Waves*, vol. 28, no. 5, pp. 363–371, 2007.

[11] "Standard ECMA-387: High Rate 60 GHz PHY, MAC and HDMI PALs ," 2010.

[12] "IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements. Part 15.3: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) Amendment 2: Millimeter-wave-based Alternative Physical Layer Extension," *IEEE Std 802.15.3c-2009 (Amendment to IEEE Std 802.15.3-2003)*, pp. c1–187, 2009.

[13] "IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements-Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band," *IEEE Std 802.11ad-2012 (Amendment to IEEE Std 802.11-2012, as amended by IEEE Std 802.11ae-2012 and IEEE Std 802.11aa-2012)*, pp. 1–628, 2012.

[14] A. Maltsev, V. Erceg, and E. Perahia, "Channel models for 60 GHz WLAN systems," *IEEE 802.11-09/0334r8*, 2010.

[15] "Report ITU-R M.2135-1: Guidelines for evaluation of radio interface technologies for IMT-Advanced," *ITU-R Recommendations and Reports, ITU, Geneva, Switzerland*, 2009.

[16] X. Ding, Z. Jianhua, G. Xinying, Z. Ping, and W. Yufei, "Indoor Office Propagation Measurements and Path Loss Models at 5.25 GHz," in *Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th*, pp. 844–848.

[17] Hittite Microwave Corporation, "HMC6000LP711E - 60 GHz Tx with Integrated Antenna," 2014.