Evaluating the Impact of User Height Variations on Outdoor-to-Indoor Propagation in Urban Macrocells and Picocells Using Ray-Tracing

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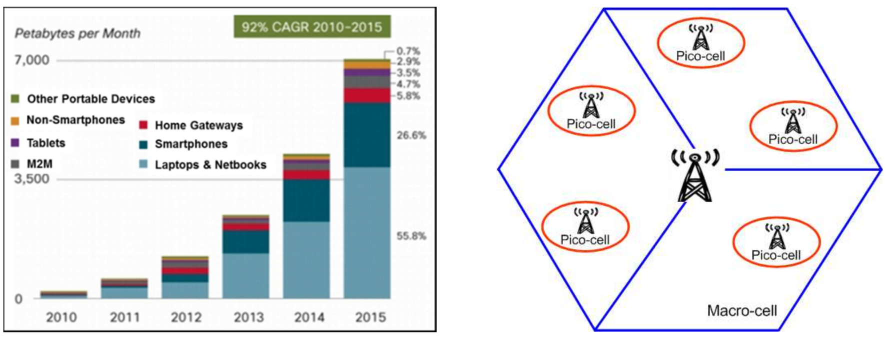
Abstract

This paper investigates Outdoor-to-Indoor (O2I) propagation at 2.6 GHz in urban macrocells (1 km radius) and picocells (150 m radius) including the effect of the user height variations on the statistics of the propagation Large-Scale-Parameters (LSPs) using 3D ray-tracing in the city of Bristol, UK. Path-loss is found to vary by up to approximately 10 dB between user height levels from first to eighth floor, and a user height-gain figure is used to parameterise it as a linear function of the user height. The statistics of the rest LSPs, which include shadow fading, K-factor, Root-Mean-Square (RMS) delay spread and RMS azimuth/elevation spread departure/arrival, are also analysed. Significant dependencies on the user height variations are noticed mainly for Line-of-Sight (LoS) macrocell links (e.g. the K-factor is shown to increase by about 11 dB in average as the user height increases from first to eighth floor).

1. Introduction

With the recent evolutionary introduction of new electronic devices such as smartphones and tablets as an integral part of our every-day life, the typical use of wireless terminals has changed from the traditional voice and messaging to high data rate demanding applications (e.g. High Definition (HD) video streaming, online gaming, social and professional networking, etc.). As illustrated in Figure 1(a), mobile data traffic for laptops, mobile phones and tablets is expected to grow at a Compound Annual Growth Rate (CAGR) of 92% from 2010 to 2015, reaching 7 Exabytes per month by 2015 [1]. Furthermore, with the recent deployment of the 4G cellular network, which offers good Quality-of-Service (QoS) for high data rate demanding applications, the use of network-connected devices in indoor environments (e.g. home or office) and not only outdoors is increasing rapidly. Urban outdoor macrocell and picocell 3-Dimensional (3D) propagation Large-Scale-Parameter (LSP) statistics based on ray-tracing have been presented in [2] and [3] respectively (with street-level users in mind). In Outdoor-to-Indoor (O2I) propagation, however, the users cannot be assumed to be positioned on street-level as a home or an office can be located at various heights above the ground.

Furthermore, the end-user experience is becoming more important, with good QoS requiring high data throughputs (system capacity), large coverage areas, link reliability, low latency, and robustness to interference between co-existing networks. Therefore, significant improvements are now required in spectral efficiency. One solution is to complement the traditional macrocell base-stations (BSs), which provide basic coverage, with a number of lower power picocell BSs in areas of high data traffic demands, thereby creating a Heterogeneous Network (HetNet) [4]. Figure 1(b) shows a schematic description of a HetNet topology.



(a) (b)

Figure 1. (a) The global mobile traffic forecast [1]; (b) Heterogeneous network topology utilising a mix of a high power macrocell basestation and lower power picocells

In order to achieve high capacities and fully exploit the benefits offered by the HetNets in the 4G cellular networks (and beyond), the wireless channel needs to be thoroughly understood, as it determines the quality of the link and hence the end-user experience. This paper investigates O2I 3D propagation at 2.6 GHz in urban macrocells (1 km radius) and picocells (150 m radius) including the effect of user height variations (from first to eighth floor level) on LSPs using ray-tracing. The rest of the paper is organised as follows. Section 2 describes the system modelling parameters. Section 3 discusses the results analysing the Path-Loss (PL) and presenting a statistical analysis of the rest LSPs, which include the K-factor, the Root-Mean-Square (RMS) Delay Spread (DS), and the RMS Azimuth/Elevation Spread Departure (ASD/ESD) and Arrival (ESA/ESD). Section 4 concludes the paper.

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2. System Modelling Parameters

In order to model the Outdoor-to-Indoor (O2I) propagation process, ray paths from the outdoor BS to the indoor user terminal were divided in three distinct parts:

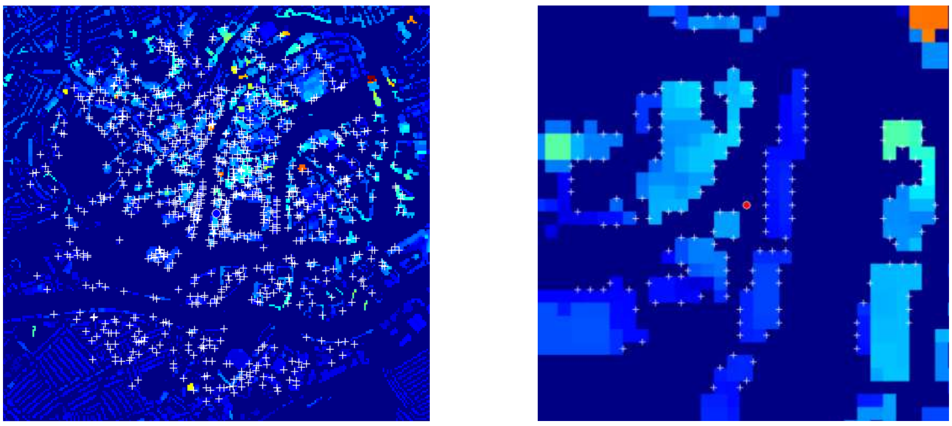
1) Outdoor propagation from the BS to the outer side of the building wall nearest to the user;
2) Propagation through the wall; and
3) Indoor propagation from the inner side of the wall to the user.

The above was performed on a per-ray basis. Equation (1) describes the total path-loss of a ray in the O2I scenario.

$$\mathrm{PL}_{total} = \mathrm{PL}_{out} + \mathrm{PL}_{tw} + \mathrm{PL}_{in} \quad (1)$$

where PL_{total} is the total PL of a ray travelling from the outdoor BS to the indoor user terminal, PL_{out} refers to the path from the BS to the outer side of the wall closest to the user, PL_{tw} is the PL introduced by the penetration through the wall and PL_{in} refers to the path inside the building from the wall to the user. The effect of the user height was investigated by placing users on the first to eighth floor of a number of buildings. A floor height of 3 m and a user height (above the floor) of 1 m were assumed. It should be noted that first floor refers to the floor at ground level. All analysis was performed at 2.6 GHz.

The first (outdoor) part of the O2I propagation was investigated using University of Bristol's outdoor 3D ray-tracing software tool [5] with a 17.6 km^2 database of the city centre of Bristol, UK. The database had a resolution of 10 m and included full terrain, building and foliage information. For the macrocell study, 23 BSs were placed on real rooftop locations with heights of 7 m to 77 m. The BS antenna was placed at a height of 3 m above clutter level in all cases in order to avoid interactions with the rooftop edges. Each BS was modelled to cover a hexagonal cell, and 900 users were randomly scattered in each cell within a radius of 1 km, as shown in Figure 2(a). All users were placed on the outer side of building walls on different floor heights (from first to eighth floor). The analysis was performed with 43 dBm BS transmit power. For the picocell study, a large number of post-mounted BSs and users were randomly scattered around the city of Bristol, resulting in 30,000 BS-to-user links. The users were placed within a radius of 150 m around the BS and were mounted on the outer walls of buildings at different floor heights. The BSs were mounted at a height of 5 m above ground level and transmitted with a power of 30 dBm. Figure 2(b) shows an example of the wall-mounted users in a picocell. It should be noted that in all cases, no antenna radiation patterns or polarisation were included in the propagation modelling in order to form a pure channel model (i.e. isotropic elements with 0 dB gain in all directions were assumed at both ends of the link). This allows any type of transmit and receive antenna pattern to be applied at a later stage as a spatial-polarisation-phase convolution process. A user receiver sensitivity of -120 dBm and a dynamic range of 25 dB were assumed. It should finally be noted that the modelling was conducted with the downlink in mind and hence departure refers to angles at the BS and arrival to angles at the side of the user. Obviously the channel model is still valid for the uplink by switching departure and arrival angles.



(a) **(b)**

Figure 2. Example of user locations on the building database raster. Buildings are colour-coded according to height. (a) Macrocell; (b) Picocell

The PL terms of Equation (1) that refer to the propagation through the wall (PL_{tw}) and to the path inside the building from the wall to the user terminal (PL_{in}) were calculated for each ray using Equation (2) and Equation (3) respectively from the ITU [6] and the WINNER [7] channel model.

$$\mathrm{PL}_{tw} = 14 + 15(1 - cos\theta)^2 \quad (2)$$

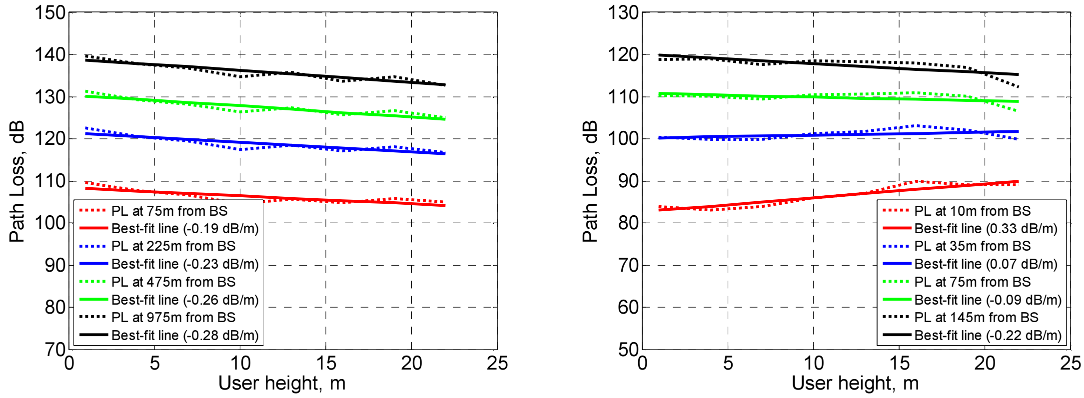
$$\mathrm{PL}_{in} = 0.5 d_{in} \quad (3)$$

where θ is the angle between the incoming ray and the normal to the wall vector, and d_{in} is the indoor distance from the wall to the user terminal. The latter was modelled as a per-user random variable uniformly distributed between 1 m and 20 m, assuming that there is always going to be a wall within an in-building distance of 20 m from every user.

It should be noted that the analysis of the results are separated in Line-of-Sight (LoS) and Non-LoS (NLoS). In O2I propagation all links are essentially NLoS. The separation of the links into LoS and NLoS refers to the outdoor part of the link from the BS to the wall.

3. Analysis of Propagation Large-Scale-Parameters

This section presents an analysis of the modelled propagation LSPs. We initially analyse the path-loss which refers to the link from the BS to the outer side of the building wall, i.e. PL_{out} in Equation (1). Figure 3 shows PL as a function of the user height for four distinct BS-to-user distances (75 m, 225 m, 475 m, and 975 m for macrocells in Figure 3(a); 10 m, 35 m, 75 m, and 145 m for picocells in Figure 3(b)). The graphs refer to the NLoS links. The best-fit lines are also illustrated. The slope of those lines is defined as the user height-gain and is expressed in dB/m as a function of the separation distance between the BS and the user [8]. A positive user height-gain indicates a proportional relationship of PL with the user height, whereas a negative user height-gain means that the relationship between PL and the user height is inversely proportional. The larger the absolute value of the height-gain, the more sensitive PL is to changes of the user height. It can be noticed that PL is decreasing with user height for all BS-to-user separation distances in macrocells (with an increasing absolute value of user height-gain). In picocells, however, PL is decreasing with user height when the user is located far from the BS and increasing when the user is close to the BS. Hence a user height-gain from -0.19 dB/m (at 75 m from BS) to -0.28 dB/m (at 975 m from BS) is noticed in NLoS macrocells, and from 0.33 dB/m (at 10 m from BS) to -0.22 dB/m (at 145 m from BS) in NLoS picocells. Table I and Table II summarise the user height-gains for LoS and NLoS macrocell and picocell links respectively for the four aforementioned distinct BS-to-user separation distances. It should be noted that the PL trends presented in this paper agree with those reported in [8].



(a) (b)

Figure 3. User height-gain at dour distinct distances from the BS in NLoS links in (a) macrocells and (b) picocells.

TABLE I. User height-gain at four distinct distances from the BS to the outdoor side of the building wall in macrocells.

	LoS / NLoS			
Distance from BS (m)	**75**	**225**	**475**	**975**
User height-gain (dB/m)	-0.10 / -0.19	-0.13 / -0.23	-0.16 / -0.26	-0.18 / -0.28

TABLE II. User height-gain at four distinct distances from the BS to the outdoor side of the building wall in picocells.

	LoS / NLoS			
Distance from BS (m)	**10**	**35**	**75**	**145**
User height-gain (dB/m)	0.21 / 0.33	0.01 / 0.07	-0.11 / -0.09	-0.21 / -0.22

The statistics of the rest LSPs were also analysed as a function of the user height. Table III summarises the mean (μ) and the standard deviation (σ) of the variables of SF, K-factor, ASD, ESD, ASA and ESA in macrocells and in picocells. Results are shown only for the first, fourth and eighth floor level. Significant dependencies on user height variations can be noticed, which are in general more obvious in the LoS macrocell links. For example, we can indicate an increase in the mean value of the K-factor in the macrocell LoS links by up to about 11 dB as the user height increases from the first to the eighth floor level. In Multiple Input Multiple Output (MIMO) communication systems, which take advantage of the multipath propagation, a high K-factor (i.e. a strong dominant component) will result in a large spread of the singular values of the channel matrix and hence the MIMO benefits on capacity will be reduced. However, a like-to-like comparison is valid only if the mean power is the same, as in many cases a strong LoS component may increase the average Signal-to-Noise-Ratio (SNR) and thus compensate for the loss in capacity. Large angular spreads (at both ends of the link) will result in uncorrelated spatial streams and therefore they are beneficial for MIMO. It was shown in [9], for example, that the use of BS MIMO antenna arrays with the elements orientated in the vertical direction results in significantly higher data rates in picocells than in macrocells due to the considerably larger elevation angular spread at the BS (a maximum RMS value of 50° in picocells compared to a maximum value of only 5° in macrocells).

TABLE III. Mean (μ) and standard deviation (σ) of LSPs in macrocells / picocells.

		1st Floor		4th Floor		8th Floor	
		LOS	NLOS	LOS	NLOS	LOS	NLOS
SF [dB]	μ	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0	0 / 0
	σ	14.6 / 13.83	10.38 / 10.39	13.2 / 12.49	10.83 / 10.76	14.55 / 13.56	9.74 / 10.44
K-factor [dB]	μ	11.71 / 11.27	7.35 / 4.45	18.46 / 11.58	10.03 / 4.67	22.91 / 13.82	7.38 / 3.7
	σ	10.45 / 10.11	11.47 / 9.14	15.34 / 12.27	14.64 / 9.95	16.29 / 11.78	13.66 / 9.4
RMS DS $\log_{10}$[s]	μ	-8.3 / -8.13	-7.47 / -7.43	-8.46 / -8.06	-7.41 / -7.34	-8.49 / -8.0	-7.09 / -7.12
	σ	0.83 / 0.65	0.74 / 0.58	0.99 / 0.72	0.89 / 0.62	1.01 / 0.63	0.77 / 0.56
RMS ASD $\log_{10}$[°]	μ	-0.34 / 0.76	0.26 / 1.02	-0.4 / 0.89	0.31 / 1.08	-0.48 / 0.99	0.51 / 1.16
	σ	0.97 / 0.91	0.89 / 0.76	1.42 / 1.01	1.05 / 0.74	1.25 / 0.80	0.89 / 0.65
RMS ESD $\log_{10}$[°]	μ	-0.88 / 0.1	-0.63 / 0.21	-1.44 / 0.29	-0.66 / 0.38	-1.69 / 0.35	-0.46 / 0.49
	σ	0.95 / 0.89	1.05 / 0.75	1.89 / 1.01	1.24 / 0.78	2.29 / 0.93	0.96 / 0.68
RMS ASA $\log_{10}$[°]	μ	0.85 / 0.88	1.06 / 1.03	0.52 / 0.9	0.92 / 0.96	0.27 / 0.74	0.91 / 0.92
	σ	0.7 / 0.62	0.57 / 0.71	0.9 / 0.68	0.7 / 0.83	0.96 / 0.74	0.64 / 0.77
RMS ESA $\log_{10}$[°]	μ	0.23 / 0.37	0.63 / 0.57	-0.49 / 0.45	0.46 / 0.6	-1.18 / 0.18	0.35 / 0.53
	σ	1.06 / 0.88	0.68 / 0.88	2.18 / 1.14	0.94 / 0.96	2.48 / 0.94	0.87 / 1.04

4. Conclusions

This paper investigated O2I propagation in urban macrocells (1 km radius) and picocells (150 m radius) including the effect of the user height variations on the statistics of the propagation LSPs. Analysis was performed at 2.6 GHz using a state-of-the-art 3D ray-tracing software tool for the city of Bristol, UK. PL was found to vary by up to approximately 10 dB between user height levels from first to eighth floor and a user height-gain figure was used to parameterise it as a linear function of the user height. It was shown that PL was decreasing with user height for all BS-to-user separation distances in macrocells (with an increasing absolute value of user height-gain). In picocells, however, PL was decreasing with user height when the user was located far from the BS and increasing when the user was close to the BS. The statistics of the rest LSPs, which included the variables of SF, K-factor, DS, ASD, ESD, ASA and ESA, were also analysed and significant dependencies on the user height variations were noticed mainly for LoS macrocell links. For example, the K-factor was shown to increase by about 11 dB in average as the user height increased from first to eighth floor.

5. Acknowledgements

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