Wang, Z., Tameh, EK., & Nix, AR. (2004). Statistical peer-to-peer channel models for outdoor urban environments at 2GHz and 5GHz. In *IEEE Vehicular Technology Conference (September 26-29, 2004 : Los Angeles, Calif.)* (pp. 5101 - 5105). Institute of Electrical and Electronics Engineers (IEEE). https://doi.org/10.1109/VETECF.2004.1405071

Statistical Peer-to-Peer Channel Models for Outdoor Urban Environments at 2GHz and 5GHz

Zhenyu Wang, Eustace K. Tameh and Andrew R. Nix
Centre for Communications Research
University of Bristol
Merchant Venturers Building, Woodland Road, Bristol, BS8 1UB, United Kingdom.
E-mail: {zhenyu.wang, tek.tameh, andy.nix}@bris.ac.uk

***Abstract*—This paper provides a new statistical propagation model that addresses a number of gaps in the area of peer-to-peer radio channel modelling in an urban micro-cellular environment. The work in this paper focuses on the 2.1GHz (UMTS) and 5.2GHz (Hiperlan/2 and 802.11a/e/h) bands and makes use of a detailed three-dimensional ray-tracing tool. Propagation analysis reveals that the standard deviation of the shadowing is actually a function of the separation distance between the transmitter and receiver. Path loss increases with lower terminal heights, as does the probability of a line-of-sight. Statistical channel models are derived that combine standard parameters such as separation distance, operating frequency and terminal height with more advanced and innovative parameters such as distance dependent shadowing and LOS probability.**

Keywords: channel model; path loss; shadowing; peer-to-peer; multihop; Ad-hoc; urban

I. INTRODUCTION

For future wireless communication systems beyond third generation networks, many researchers are considering a combination of peer-to-peer connectivity with traditional cellular solutions to improve coverage, reduce transmit power, and ultimately to provide ubiquitous high capacity connectivity [1-4]. The need to evaluate the performance of such systems in an urban environment calls for appropriate radio channel models. To meet this aim, this paper presents a new statistical peer-to-peer channel model for use in dense urban environments.

Although statistical models for high mounted base station (BS) to mobile (MS) links (BS-MS) already exist in the literature [5, 6], no such models appear for peer-to-peer (MS-MS) links. Channel characterizations for MS-MS links are expected to be significantly different to BS-MS links because of the low terminal heights and the relatively short propagation distances involved. In the case of structured multi-hop networks [4], there is a critical need for accurate statistical channel models for low mounted relay node (RN) to MS links (RN-MS), RN links (RN-RN) and BS links (BS-RN). Over the last two years, several reports [7, 8] have tried to extract the channel characteristics for RN-MS and MS-MS links. However, a detailed investigation of such channels in an outdoor environment at 2.1GHz and 5.2GHz is not present in the literature and this gap is addressed by this contribution.

In this paper, a statistical channel model for low mounted (relative to ground height) wireless links in urban environments is presented. The model is developed based on the statistical analysis of predicted channel data from a fully three-dimensional deterministic propagation mode for the centre of Bristol. Channel properties such as *Path Loss*, *Shadowing Standard Deviation, LOS/NLOS* probabilities and the narrowband *K-factor* are considered for BS-MS, BS-RN, RN-MS, RN-RN and MS-MS links. The proposed models are particularly attractive for use in system level simulations that incorporate relaying, ad-hoc extensions and/or ODMA networks.

The remainder of this paper is organized as follows: In section II, the concept of the channel model is described; in section III, the 3-D ray model used to obtain channel data is introduced together with its simulation settings. Data analysis and the channel model parameters are given in section IV, and a number of concluding remarks are presented in Section V.

II. CHANNEL MODEL

A. Radio Channel Type

Radio propagation depends on the topographical and electrical features of the surrounding objects [15]. Radio channel types are classified by 'general' propagation conditions, defined by the operating frequency, the Tx/Rx heights, the radio environment and the LOS/NLOS condition. The latter parameter indicates whether a direct or dominant propagation path exists between the Tx and Rx.

The work in this paper focuses on modelling the radio channels for a multihop/ad-hoc network in urban environments at 2GHz and 5GHz. A total of 10 radio channel types are defined: *BS-RN LOS/NLOS, BS-MS LOS/NLOS, RN-RN LOS/NLOS, RN-MS LOS/NLOS and MS-MS LOS/NLOS*. All the channel studies and model parameters in this paper are grouped under the above categories.

B. Path Loss Model

The following slope/intercept statistical model [7, 9, 10] is used to model the mean outdoor path loss:

$$L_1[dB] = b + 10n\log_{10}(d) \qquad (1)$$

This work was performed under the IST-2001-32549 ROMANTIK project

where L_1 is the mean path loss averaged over a large number of Rx and Tx locations in the same radio environment, d denotes the transmission separation distance in meters, n is the attenuation (slope) exponent and b is the path loss at a reference distance of 1 meter. Since b is a function of frequency f, to apply the above model to a range of operating frequencies, b can be represented using following equation [5]:

$$b = b_0 + 20\log_{10}\left(f/MHz\right). \tag{2}$$

C. Shadowing Model

Path loss at a fixed separation distance depends on the particular objects that lie between the Tx and Rx. Variations in the mean path loss for a given separation distance are modelled as a shadowing process. From various experimental results, it has been shown that the shadowing process can be characterized by a lognormal distribution (a normal distribution in dB) over a large number of measurement locations with the same Tx-Rx separation distance [5,11].

$$L_{Shadow}[dB] = N(\mu, \sigma_{Shadow}), \quad \mu = 0. \tag{3}$$

where $N(\mu, \sigma)$ is a normal distribution with mean μ and standard deviation σ.

D. Fast Fading Model

Fast fading represents the rapid amplitude variations of a received signal for movements in the order of a wavelength, which occur due to the constructive and destructive summation of multipaths in the radio channel.

In a narrowband model, the most common model for *fast fading* is Rayleigh (NLOS) and Rician (LOS). The ratio between the expected power of the dominant path ρ^2 and the power of the Rayleigh components $2\sigma^2$ is often expressed by the *Ricean K-factor*: $K_0 = \rho^2 / 2\sigma^2$.

III. RAY MODEL SIMULATION

For peer-to-peer links it is extremely difficult to obtain sufficient data samples by means of measurements alone. This arises since it is impractical to measure a large number of mesh links between MSs, BSs and RNs. To overcome this problem, best fit statistical models are developed based on the data generated from a previously validated fully three-dimensional deterministic propagation model [12]. This model uses geographic data (terrain, building, foliage and ground cover data) to predict power as well as time, frequency and spatial dispersion in the radio channel. The model was developed at the University of Bristol and has been validated for transmitter (Tx) and receiver (Rx) locations above, below and at rooftop in urban environments at 2GHz and 5GHz [13, 14]. For the Bristol area, the mean error in average power was less than 4.5dB and the rms. error was less than 7.5dB.

Simulations are conducted over a 1.4km x 1.4km area of central Bristol. The urban environment is typical of European cities with typically heights in the order of 3 stories. The average building height and road width for this region was 12m and 20m respectively. The test area also includes several hills with terrain height variations in the order of 60 meters. The height of the antennas was set to 15m, 5m and 1.5m for BS, RN and MS nodes respectively. A vertical dipole antenna was assumed at both the Tx and Rx. Full three dimensional antenna patterns were incorporated into the model and features such as polarization were included in the final power prediction.

It is well known that the channel properties in a terrestrial environment are highly dependent on the location of the Tx and Tx [6, 15]. To generate a meaningful statistical model, a total of 26 different Tx sites were used. These sites were spread over the entire map area, as shown in Fig. 1. Rx points were spread over a 1.2km x 1.2km grid based on the map center. The last 200 meters at the edge of the database was avoided to prevent inaccuracies due to a lack of surrounding buildings and terrain data. The spacing between points was set to 11m (a value based on a compromise between computer run time and dataset size). Excluding building locations, where the receiver could not be placed, a total of 26 x 9,003 Tx-Rx locations were analyzed for each of the defined link types. Figure 2 shows an example of the predicted local mean power for a MS-MS link at a given transmit location.

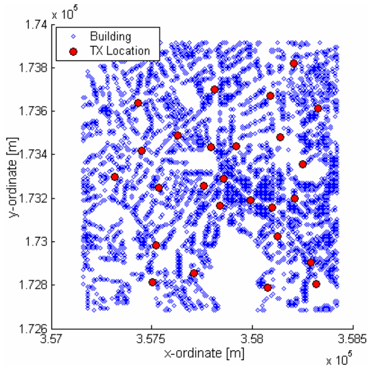


Figure 1. Tx location settings

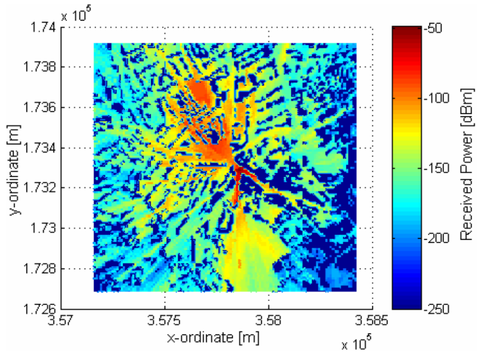


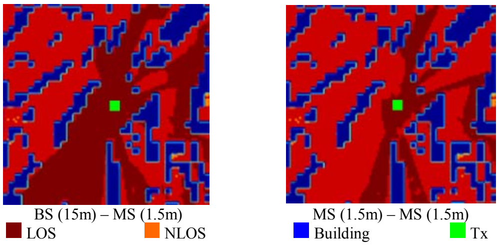
Figure 2. Example of MS-MS signal coverage

IV. CHANNEL CHARACTERIZATION

A. LOS Probability

To distinguish the likelihood of LOS and NLOS conditions, the geographical information (including detailed terrestrial and building information) is used. Figure 3 shows the LOS coverage for different Tx heights at the *same* location.

It can be seen that as the Tx height is reduced from 15m (BS-MS) to 1.5m (MS-MS), the signal propagation paths are affected not only by the surrounding buildings in the vicinity the Tx, but also by the terrain. The peer-to-peer link could be NLOS even when no buildings lie in the propagation path.



BS (15m) – MS (1.5m)   MS (1.5m) – MS (1.5m)

Figure 3. LOS and NLOS coverage for different TX heights

Figure 4 shows the LOS conditional probabilities as a function of the distance between the Tx and Rx. This data was obtained by averaging the LOS/NLOS statistics from 26 Rx grids (one for each of the Tx locations shown in Fig. 1). From Fig. 4 it can be seen that when the separation distance is less than 10m, the LOS probability is 1 (for this particular database and set of locations). This value broadly corresponds to the value of the street width, which lies in the region of 10-20m.

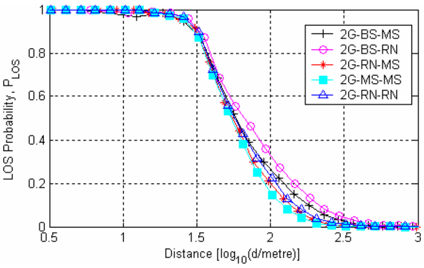


Figure 4. LOS Probability versus Distance

The impact of Tx height on the probability of a LOS connection can also be observed. A lowering of the LOS probability for low mounted transmitters will significantly increase the expected path loss for longer range peer-to-peer connections.

B. Path Loss

Figure 5 shows a scatter plot for the Rx power versus distance for the MS-MS channel at 2.1GHz, where LOS and NLOS cases are distinguished using red and gray spots respectively. A sudden drop in received power from LOS to NLOS can be clearly observed in the figure when the separation distance is less than 100m. As the distance increases, even in LOS conditions, the Rx sometimes experiences high path loss. This is due to the direct propagation path being 'softly' obstructed by trees, instead of the buildings or terrain considered in our previous LOS definition. Hence, additional attenuation (as a result of foliage loss in the ray model) is seen in these cases. These types of partially obstructed link are sometimes referred to as Quasi-Line-of-Sight QLOS for outdoor propagation studies [6, 16] and Obstructed LOS (OLOS) for indoor analysis [17]. However, the mean path loss for LOS can still be modelled by the free space path loss, with $b_0 = -27.6$ and $n = 2$. Further path loss discussion can be found in the following subsection.

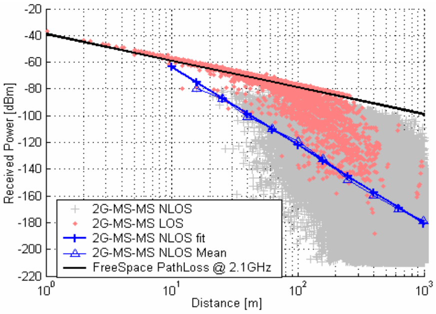


Figure 5. Scatter plot of the received power versus distance

For NLOS locations, the distance dependent mean path loss was extracted by averaging all the path loss values from the 26 grids. The Least Squares (LS) algorithm was used to derive (fit) the mean path loss model parameters in equation (1) and (2). The estimated model parameters for all Tx/Rx combinations are listed in Table I, and the predicted mean path loss curves are plotted in Fig. 6. From this figure we can see that when the Tx antenna height drops from 15m to 5m and 1.5m, i.e. from above the average building rooftop to below the average rooftop height, the mean path loss shows a significant increase, which implies a significant decrease in received power. The path loss increases faster with distance with a lowering of antenna height.

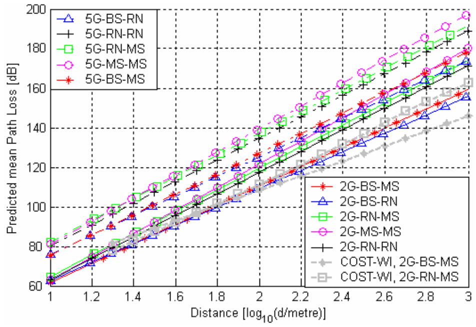


Figure 6. Scatter plot of the received power versus distance

Figure 6 also shows the predicted path loss curve for the well known COST-Walfisch-Ikegami-Model (COST-WI) with parameter values corresponding to the ray model setting. Comparing the new model with the COST-WI model, in the case of BS-MS links, the two models give very similar results when the separation distance is less than 200m, while the new model gives greater path loss when the separation distance increases. The difference reaches 10dB at 1km. In the case of the RN-MS link, the new model always gives a higher value of path loss. Note: COST-WI is not valid for 5GHz and peer-to-peer communication links.

TABLE I. ESTIMATED PARAMETERS FOR NLOS PATH LOSS MODEL

NLOS	**2GHz**		**5GHz**	
	b_0 *(dB)*	*n*	b_0 *(dB)*	*n*
BS-RN	-50.15	4.64	-47.59	4.92
BS-MS	-53.37	4.88	-50.19	5.14
RN-RN	-57.48	5.42	-48.71	5.44
RN-MS	-56.40	5.47	-46.78	5.48
MS-MS	-62.01	5.86	-51.22	5.82

C. Shadowing

The shadowing data was calculated by subtracting the local mean power from the distance dependent mean path loss found in the previous study. The simulated data showed a good agreement with the lognormal distribution assumed for NLOS conditions, as shown by the strong Gaussian fit in Fig. 7. However, for LOS locations, mainly due to waveguide effects in the streets, for many Tx locations the path loss is 2dB less than that expected for free space. The shadowing in LOS conditions appears to follow a more uniform distribution with a bias toward negative values. Moreover, from Fig. 5 it can be seen that the variability in the shadowing process tends to increase with increasing distance. This implies that the shadowing standard deviation is distant dependent. A plot of the standard deviation σ_{Shadow} (STD) versus separation distance can be found in Fig. 8 and 9 for NLOS and LOS conditions respectively.

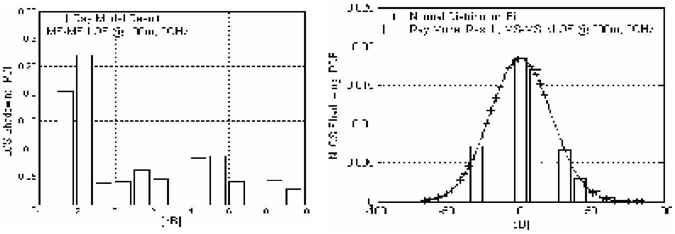


Figure 7. Shadowing PDF of LOS and NLOS , MS-MS at 2.1GHz

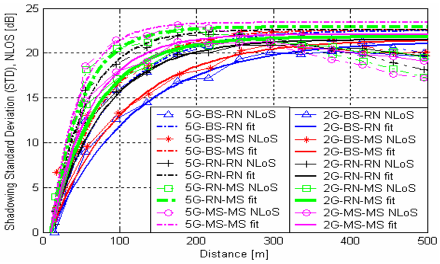


Figure 8. Shadowing Standard Deviation (STD), NLOS

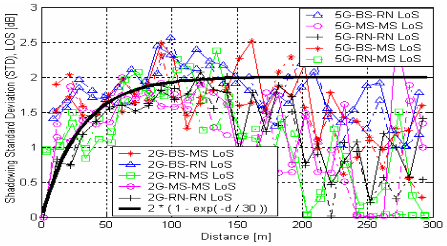


Figure 9. Shadowing Standard Deviation (STD), LOS

For the 2GHz NLOS data, the standard deviation increases from less than 5dB at a distance of around 20m, to more than 20dB for a distance greater than 200m (RN-RN, RN-MS, MS-MS links) and 300m (BS-RN, BS-MS links). For low mounted Tx and Rx nodes a higher observed standard deviation was seen. The 5GHz frequency band shows a slightly larger shadowing standard deviation as compared to the 2GHz band. It can be seen from these figures that the shadowing standard deviation reaches a peak at a certain critical distance and then starts to fall. At large distances the path loss at many Rx locations is so great that the received power falls below the simulator threshold (which is set at –210dBm). Locations beyond this threshold are not included in the analysis. It can be seen that the maximum σ_{Shadow} is beyond 20dB, which is far higher than that reported by other authors [6]. This could result from 1) the hilly terrain of Bristol and 2) the Rx being located at all possible positions in the grid, including those very close to building surfaces where deep shadow fading can occur. Finally, it has been found that the distance-dependent standard deviation can be well modelled using the following function:

$$\sigma_{Shadow}(d) = S \cdot \left(1 - e^{\frac{-(d-d_0)}{D_S}}\right) \tag{4}$$

where d represents the distance between the Tx and Rx, S is the maximum standard deviation, D_S is the growth distance factor in meters, and $d_0 = 10m$. The least squares error estimated parameters can be found in Table II.

TABLE II. ESTIMATED PARAMETERS FOR NLOS SHADOW STD MODEL

NLOS	**2GHz**		**5GHz**	
	S(dB)	*D_S(m)*	*S(dB)*	*D_S(m)*
BS-RN	21.3	110	22.5	75
BS-MS	21.5	96	22.6	67
RN-RN	21.5	69	22.6	46
RN-MS	21.8	59	22.9	40
MS-MS	22.1	53	23.4	36

For the LOS cases, the standard deviation increases from 0dB at zero distance to around 2dB at 100m. Since the LOS standard deviation for the different antenna heights and operating frequencies is small, the same model can be used, i.e. $S = 2dB$ and $d_0 = 0$m in (4) for all links and bands.

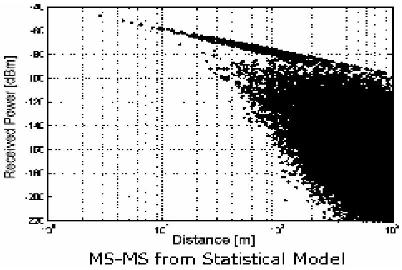


Figure 10. Predicted data from proposed model , MS-MS, grid mode

Figure 10 shows an example of the regenerated path loss statistics using distance-dependent shadowing model and the proposed LOS/NLOS probabilities. The model can be seen to provide a good 'fit' with the original data (Fig. 5).

D. K-factor

The narrowband Ricean K-factor has been extracted and is plotted in Fig. 11. For LOS locations, the median K-factor drops with increasing Tx-Rx distance. This is due to the fact that the signal power decay is logarithmic with distance. With the same excess delay, the power ratio of the multipath components to the direct path is much smaller at large Tx-Rx distances compared to small distances.

Figure 12 shows the mean narrowband K-factor versus distance for all link types at both 2.1GHz and 5.2GHz. The best fit parameter for the mean K-factor is grouped in Table III. It was found that the K-factors for 5GHz are much larger than the corresponding values at 2GHz, which occurs because of the faster power decay rate at the higher frequency. It can also be seen that lower antenna heights result in smaller K-factors. The data analysis shows that the variation in K-factor is consistent for all distances and the STD is approximately 10dB. Let ΔK_{LOS} represents the difference between the Ricean K-factors and their mean values; it has been found that ΔK_{LOS} follows a Normal distribution (Fig. 13 (a)).

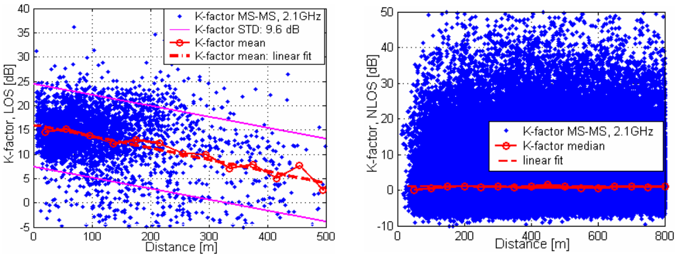


Figure 11. K-factor versus distance. LOS and NLOS

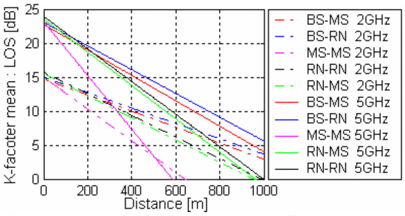
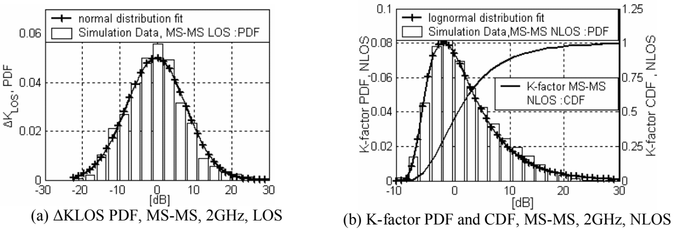


Figure 12. Mean K-factor versus distance (LOS)



(a) ΔKLOS PDF, MS-MS, 2GHz, LOS

(b) K-factor PDF and CDF, MS-MS, 2GHz, NLOS

Figure 13. K-factor PDF and CDF, MS-MS at 2GHz

In the case of NLOS, the median K-factor value was found to lie between 0 and 1dB for all separation distances, with a STD of 6dB. Figure 13 (b) shows the PDF and CDF of the NLOS K-factors for MS-MS links at 2GHz. Although the median value of the K-factor is about 0dB, there are more than 10% of NLOS Rx locations with a K-factor greater than 10dB. Furthermore, the K-factor variation follows a lognormal distribution and can be modelled using:

$$K_0(dB) = \log N(\mu_K, \sigma_K) - 10 \qquad (5)$$

where $logN(\mu, \sigma)$ is a lognormal distribution with corresponding mean μ and standard deviation σ. The estimated parameters are listed in Table IV.

V. CONCLUSIONS

The channel model presented in this paper improves the accuracy of peer-to-peer channel power prediction in urban environments by using more advanced distance dependent shadowing, LOS probability and narrowband K-factor models. The proposed statistical models, incorporating the spatial correlation model for peer-to-peer channels that were developed within the same project framework [18], provides a complete solution to the problem of radio channel modelling in system level simulations that incorporate multi-hop/ad-hoc and fixed relay network elements in an urban environment in the 2-5 GHz range.

TABLE III. ESTIMATED PARAMETERS FOR LOS K-FACTOR MODEL

NLOS	**2GHz**		**5GHz**	
	b_K	n_K	b_K	n_K
BS-RN	15	0.012	23	0.018
BS-MS	15	0.012	23	0.018
RN-RN	15	0.015	23	0.023
RN-MS	15	0.015	23	0.023
MS-MS	15	0.019	23	0.029

TABLE IV. ESTIMATED PARAMETERS FOR NLOS K-FACTOR MODEL

NLOS	**2GHz**		**5GHz**	
	μ_K	σ_K	μ_K	σ_K
BS-RN	2.43	0.52	2.53	0.50
BS-MS	2.40	0.51	2.50	0.49
RN-RN	2.38	0.50	2.47	0.47
RN-MS	2.38	0.48	2.46	0.46
MS-MS	2.36	0.48	2.43	0.45

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