Line-of-Sight Probability for Urban Microcell Network Deployments

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***Abstract*—In this paper we present a new line-of-sight probability model for the urban micro cellular deployment scenario. This study utilises a high resolution 3D model of central London to conduct large scale ray-tracing of direct propagation paths between neighbouring lamp posts. These serve as a representation of mmWave self-backhauling small cells such as 3GPP integrated access and backhaul nodes. The statistical properties of the propagation paths are assessed against recognised line-of-sight probability models as a function of the distance between transmitter and receiver. Contributions as outlined in this paper have application in analytical studies aiming to understand the statistical characteristics of unobstructed high frequency 'access' links between microcell sites and end users as well as 'transport' backhaul links between neighbouring microcell sites.**

***Index Terms*—mobile network, deployment modelling, millimeter wave (mmWave), integrated access and backhaul,line-of-sight probability**

I. Introduction

Capacity growth in mobile networks can fundamentally be achieved through investment in either new spectrum or improved spectral efficiency. Increasing cell density increases spectral efficiency but is often challenging from a cost perspective for traditional macrocell deployments - particularly in urban/metropolitan environments [1]. For this reason, it is recognised that the use of low power street level small cells close to the end user allows for improved signal quality and spectral reuse (owing to the limiting street canyon propagation characteristics). It also offers the potential for simplified and lower operational cost resulting from fewer landlords - i.e. local authorities who owns suitable street infrastructure sites such as lamp posts.

The application of mmWave FR2 bands (24.25 – 52.6 GHz) in mobile networks fits well with the street level deployment model referred to in 3GPP and ITU as urban microcell (UMi) [2]. In particular, analytical models such as the line-of-sight (LOS) probability model, although frequency independent, align well with the challenging propagation characteristics of mmWave bands which are predominately characterised by the unobstructed line-of-sight component [3]. The marrying of these characteristics make application of mmWave small cells a good fit for the UMi deployment environment.

Technology developments in 5G NR such as integrated access and backhaul (IAB) allow for simplified deployment of microcells through the standardisation of a self-backhauling multi-hop architecture aimed at reducing the cost and complexity of street level deployments. Such an approach addresses the backhaul requirement whilst also removing dependence on costly new street level fibre backhaul where often the necessary road closures and street works are cost and time prohibitive. Similar initiatives such as LTE relay have previously been standardised in 3GPP release 9 [4] but have failed to gain traction primarily due to limited capacity (especially within a half-duplex multi-hop scenario) in bands below 6 GHz. The standardisation of mmWave FR2 bands make the IAB specification a more credible solution for multi-hop and self-backhauling small cells [5].

As part of the IAB specification, each IAB node is built on two distinct radio interface functions; a 'transport' function known as Mobile Termination (MT) which is used to maintain a wireless 3GPP F1 midhaul interface towards an upstream a IAB donor cell, and an 'access' function or Distributed Unit (DU) for maintaining a 3GPP Uu interface towards connecting user equipment (UE) or downstream MTs of other IAB nodes [6]. The line-of-sight probability model is valuable in analytical deployment studies of such technologies as an accurate line-of-sight probability description can provide a theoretical analysis of a mmWave IAB node access coverage as well as transport.

In this work, we construct the line-of-sight probability functions representative of lamp post mounted IAB nodes in a 3D UK urban environment outlined in Section II. The line-of-sight statistics of simulated mmWave IAB nodes mounted on real lamp posts are outlined in Section III for the transport function scenario where endpoints are other IAB nodes mounted on the top of other lamp posts. In Section IV for the access function scenario, the endpoint is a UE at a height of 1.5 m. Both access and transport scenarios are assessed against recognised UMi LOS probability models such as those adopted by 3GPP. A new model definition is proposed in Section V with optimised fitting parameters derived from the UK urban environment for both scenarios.

A. UMi Line-of-Sight Probability Models

The basic LOS probability model describes the likelihood Pr_{LOS} of an endpoint (Rx) being in clear LOS of the base station (Tx) as a function of the two dimensional distance d_{2D} between them. The UMi definition is a derivative of the urban

TABLE I: Microcellular Line-of-Sight Probability Models.

Model	Definition	Parameters
3GPP (UMi) [7]	$Pr_{LOS} = \begin{cases} 1, d_{2D} \leq 18m \\ \left[\frac{d_1}{d_{2D}} + \exp\left(-\frac{d_{2D}}{d_2}\right)\left(1 - \frac{d_1}{d_{2D}}\right)\right], 18m < d_{2D} \end{cases}$ (1)	$d_1 = 18$ $d_2 = 63$
d_1/d_2 (UMi) [8]	$Pr_{LOS} = \left(\min\left(\frac{d_1}{d_{2D}}, 1\right)\left(1 - \exp\left(-\frac{d_{2D}}{d_2}\right)\right) + \exp\left(-\frac{d_{2D}}{d_2}\right)\right)$ (2)	$d_1 = 20$ $d_2 = 39$
NYU Squared (UMi) [9]	$Pr_{LOS} = \left(\left(\min\left(\frac{d_1}{d_{2D}}, 1\right)\left(1 - \exp\left(-\frac{d_{2D}}{d_2}\right)\right) + \exp\left(-\frac{d_{2D}}{d_2}\right)\right)\right)^2$ (3)	$d_1 = 22$ $d_2 = 100$

macrocell (UMa) case but where the base station antenna height is below the height of the surrounding buildings. In the 3GPP definition this is applicable to scenarios where the base station or transmitter is 10 m or below. The currently recognised 3GPP LOS probability model (1) makes up part of the 3D channel model definitions in [10] and is based on the two-dimensional ITU UMi model in [2]. Unlike the UMa definition, early ray-tracing simulations of simulated city environments suggested little impact to the LOS probability from the UMi endpoint height [11] and so the UMi definition does not include provision for endpoint height variation.

A number of revisions to the 3GPP base model have been subsequently proposed principally built on optimisation of the curve fitting parameters d_1 and d_2. The 'd_1/d_2' model (2) proposed by the 5G Channel Model Group in [8] revises the 3GPP fitting parameters to $d_1 = 20$ and $d_2 = 66$ based of minimisation of the mean squared error (MSE) for a range of measurement campaigns contributed by the authoring research groups. In addition, the 'NYU Squared' model (3) in [9] is often cited in LOS probability studies where the same base model is updated with a squaring term which permits a greater resolution when fitting to measurement data, here the default fitting parameters proposed are $d_1 = 22$ and $d_2 = 100$. Each of these LOS probability models are outlined in Table I and are assessed as part of the environmental simulation analysis in Section III and IV.

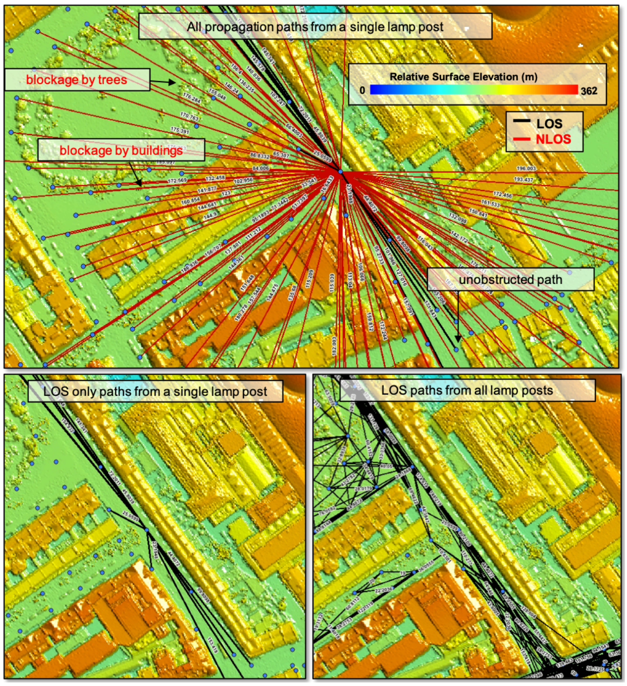

Fig. 1: DSM line-of-sight discovery.

II. Simulation Environment

In order to analyse the LOS propagation statistics of urban street canyons, a high resolution 3D urban environment was built using publicly available LiDAR surveys [12]. A number of smaller LiDAR surveys of resolutions 0.25 m, 0.5 m and 1 m were re-sampled into a single digital surface model (DSM) where the raster resolution was 0.25 m. Central London was chosen as a representative urban environment where the 3D DSM was augmented with real (BT/EE) base station sites at their correct height [13] as well as lamp post locations also at their correct height gathered from local authorities. Across the environmental model, all sites with an inter-site distance of 500 m or less were isolated as 'urban' cells (a total of 335 UMa cells) and the propagation paths between lamp posts within these urban coverage areas analysed as a deterministic dataset to understand the UMi LOS probability distribution. A ray-tracing methodology was used where all the possible direct propagation paths between each urban lamp post and any surrounding lamp posts within a 200 m radius (the inter-site distance assumed by 3GPP for UMi cells) analysed. In total, 837,687 direct propagation paths from 17,698 lamp posts were studied across the central London environment. Fig. 1 outlines a 2D view of the model as LOS and non-LOS paths are classified for a single lamp post and then iterated for the full data set to build an adjacency database of valid LOS paths and path distances between all lamp posts.

III. UMi Line-of-Sight Probability - Transport Node

In the transport node scenario, where the LOS path represents an x-haul transmission link between neighbouring IAB nodes, the LOS paths are calculated between the maximum heights of individual lamp posts. The mean height of the urban lamp posts in the DSM environment is 5.5 m with a statistical mode of 6 m [14]. The LOS PDF is constructed by binning all propagation paths over the entire study area by path distance. For each x-axis bin, a constant number of paths is maintained resulting in a non-uniform x-axis sample interval rather than a uniform sampling approach in order to avoid any path distance intervals with statistically too few samples. Each constant sample interval is a ratio of the number validated LOS paths over the 3D DSM to non-LOS paths blocked by obstructions in the urban environment.

Results for LOS probability across all the UMi lamp post sites in the study area are outlined in Fig. 2. The existing published models relevant to the UMi scenario from Table I are also overlaid using both the recommended values for the parameters d_1 and d_2, as well as optimised values achieved through minimisation of mean squared error (MSE) to the DSM data which are also summarised in Table II. Whilst the default d_1 and d_2 parameters for each model demonstrate a poor fit to the simulation data set, the optimised fitted values show very good agreement with a MSE of 0.1 or lower. This highlights the fact that the fundamental base model on which all the models definitions are derived is sound and appropriate for the UMi LOS probability curve of a real UK urban environment. The 3GPP definition demonstrates a higher MSE relative to the other models primarily due to the upper bounding constraint of d_{2D} below 18 m. Investigation of short propagation paths have shown there are still a significant number of non-LOS paths within this range typically resulting from road corner junctions and foliage blockage. The upper bounding condition of the d_1/d_2 and NYU Squared models reduce this bounding effect below 18 m providing a more appropriate fit to the underlying data. Statistically, 16% of all neighbour propagation paths of a UMi site in the central London study area are LOS.

TABLE II: UMi LOS Results - Transport Node Scenario.

Model	Parameters		MSE
3GPP (UMi) [7]	Default	$d_1 = 18$ $d_2 = 36$	1.04
	Best Fit	$d_1 = 7$ $d_2 = 37$	0.10
d_1/d_2 (UMi) [8]	Default	$d_1 = 20$ $d_2 = 39$	1.67
	Best Fit	$d_1 = 6$ $d_2 = 40$	0.02
NYU Squared (UMi) [9]	Default	$d_1 = 22$ $d_2 = 100$	1.66
	Best Fit	$d_1 = 5$ $d_2 = 90$	0.03

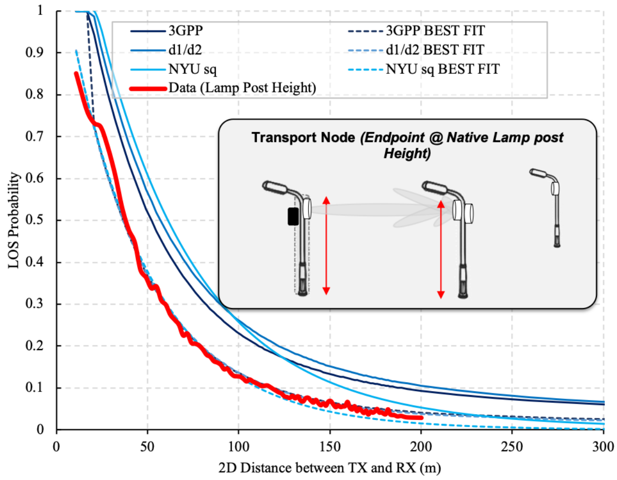

Fig. 2: LOS probability of urban lamp posts.

IV. UMi Line-of-Sight Probability - Access Node

In the access node scenario, we consider the LOS PDF where the endpoint is user equipment at a height of 1.5 m close to the lamp post data point. The same methodology as that used in the transport scenario is applied with the same dataset, the transmitter end of the propagation path is still at the native height of each lamp post but the receiver end is reconfigured for a constant height of 1.5 m above ground. This configuration represents the 3GPP Uu interface of an IAB node which is servicing mobile terminals in the street where it is assumed that the inter lamp post propagation paths are broadly representative of LOS end user coverage.

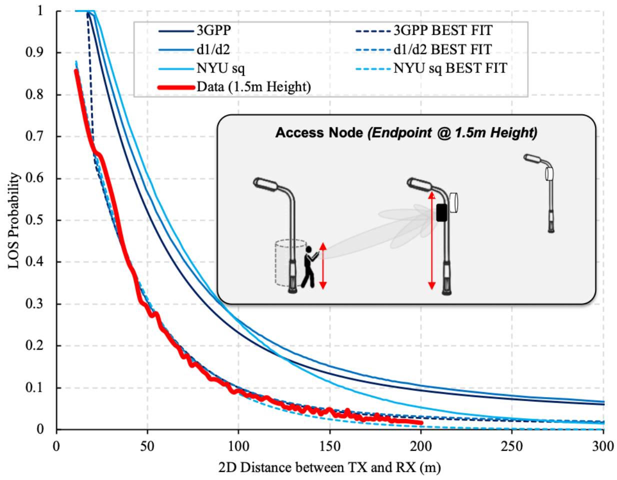

Fig. 3: LOS probability of urban lamp posts.

The simulation results are presented in Fig. 3 and again the existing published UMi models in Table I overlaid. Although the access scenario (where the propagation path represents a street level base station to UE path) is the primary scenario considered in published models they again demonstrate a relatively poor fit to the results data with the default d_1 and d_2 parameter values. The decay profile does however align well with the simulation data set and a very good agreement ≤ 0.11 MSE can be achieved through optimisation of the fitting parameters. A summary of the results are highlighted in Table III which again shows the d_1/d_2 and NYU Squared definitions providing best fit when new parametrisation is adopted. In total 12% of the propagation paths were classified as LOS in the access node scenario.

TABLE III: UMi LOS Results - Access Node Scenario.

Model	Parameters		MSE
3GPP (UMi) [7]	Default	$d_1 = 18$ $d_2 = 36$	1.94
	Best Fit	$d_1 = 5$ $d_2 = 34$	0.11
d_1/d_2 (UMi) [8]	Default	$d_1 = 20$ $d_2 = 39$	2.79
	Best Fit	$d_1 = 5$ $d_2 = 34$	0.02
NYU Squared (UMi) [9]	Default	$d_1 = 22$ $d_2 = 100$	2.79
	Best Fit	$d_1 = 5$ $d_2 = 75$	0.02

V. Impact of Street Level Endpoint Height

A results analysis of the transport and access node scenarios in Section III and IV demonstrates similar exponential decay profiles but a clear distinction in the PDF curve highlighting the need for different parametrisation. The origins of the UMi LOS probability model are based on similar ray-tracing methodologies which suggested little impact of end-point height. The finding in this paper suggest that when considering the model as a purely access orientated scenario (i.e. to UE terminals) where only small variations of UE height are expected this is still a valid assumption. However, when broadening the model application to cover alternative deployment scenarios such as the transport or inter-UMi paths there is a need to defined parameter sets differently.

In the urban street canyon environment, the transmitting endpoint is considered to be below that of the surrounding building height and as such the difference between transport and access scenarios can be assumed independent of building properties. The use of common data points in this study also isolate any impact from the layout of the urban street canyons. As such the differences observed between LOS paths from the top and bottom of the lamp post can be attributed entirely to the impact of street level clutter such as foliage and other street furniture where this impact is low but not negligible. As such it is prudent to differentiate these two sub cases of the UMi LOS probability model which can also be considered the upper and lower bounds of the general UMi LOS probability model for the UK urban environment. A 'BT UMi' definition of the UMi LOS probabilty model is proposed in (4) based on the d_1/d_2 definition but with revised parameters for the upper (transport) and lower (access) bounds of the model. The PDF of both curves against the DSM data sets are shown in Fig. 4 and the $d_1 d_2$ optimisation parameters summarised in Table. IV.The

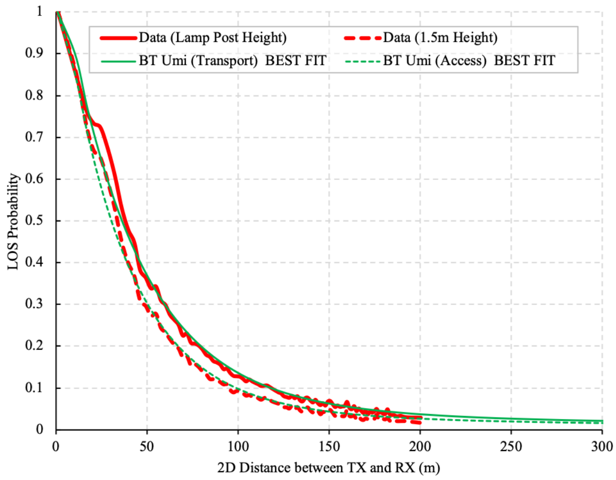

Fig. 4: BT UMi LOS probability model.

proposed model aligns well with the DSM dataset achieving a MSE of 0.2 for each case.

$$Pr_{LOS} = \left(\min\left(\frac{d_1}{d_{2D}},1\right)\left(1-\exp\left(-\frac{d_{2D}}{d_2}\right)\right)\right. \\ \left. +\exp\left(-\frac{d_{2D}}{d_2}\right)\right) \tag{4}$$

TABLE IV: Parameterisation of the BT UMi LOS Probability Model.

Model	Parameters		MSE
BT UMi LOS	Access	$d_1 = 5$ $d_2 = 34$	0.02
	Transport	$d_1 = 6$ $d_2 = 40$	0.02

VI. Conclusions

In this paper we evaluate the LOS statistical channel model for urban micro cellular deployments in an urban environment. Findings are built on a large scale deterministic methodology using a high resolution 3D environmental model of central London with real lamp post locations. The results of a LOS propagation path analysis from urban lamp post sites have shown that existing analytical probability models such as those adopted by 3GPP and ITU are not appropriate for characterising a UK urban microcell environment. Although existing models definitions have been shown to be suitable when optimised, the default fitting parameters result in a poor fit to the experimental dataset highlighting the need for a new model definition. As a result, an alternative model definition is proposed in this paper based on the 5GCM $d_1 d_2$ model but with new parameter values.

To date, published models have focused solely on the endpoint being a UE and have made no provision for variation in the height attributes of the endpoint. Crucially, in this study the development of a high resolution environmental model sufficient to accurately model small scale street level blockages pertinent to high frequency mmWave propagation paths allow self-backhauling deployment architectures such as IAB to be studied. Results have shown that the inter-UMi (transport) propagation path between the tops of neighbouring lamp posts has a 2% higher LOS probability compared with the UMi to UE (access) propagation paths close to ground level. Parametrisation of these two scenarios are derived as part of the proposed BT UMi LOS probability model which contributes new insight into the upper and lower bounds of the LOS probability for lamp post mounted radio equipment. Further work based of the discovered LOS propagation paths in the DSM will be studied to quantify the complementary characteristics of mmWave multi-hop and mesh wireless x-haul solutions for dense network deployments.

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