Urban Line-of-Sight Probability for mmWave Mobile Access and Fronthaul Transmission Hubs

Dave Townend*, Stuart D. Walker†, Adrian Sharples‡, Andy Sutton§
*BT Labs, Adastral Park, Martlesham, UK, dave.townend@bt.com
†University of Essex, Wivenhoe Park, Colchester, UK, stuwal@essex.ac.uk
‡BT Labs, Adastral Park, Martlesham, UK
§BT Technology, London, UK

***Abstract*—The line-of-sight (LOS) probability model is a fundamental tool in evaluating high frequency (mmWave) mobile network deployments. This paper utilises a large scale 1875 sq km, high resolution environmental model of representative UK cities to analyse the statistical LOS properties of urban macro (UMa) base stations. The digital environment results are used to evaluate the accuracy of analytical probability models such as those published in industry standard guidelines. A LOS probability distribution for UK street lamp posts is presented to quantify the feasibility of wireless fronthaul connectivity from macro cell hub sites to new street level small cells. In addition, generalised LOS results are presented at a range of end point heights permitting a new UMa model to be proposed. The new model addresses shortcomings of existing models whilst describing the likelihood for LOS conditions between macro sites and street canyon end points at heights of up to 10 m.**

***Index Terms*—cellular network, deployment modelling, statistical channel modelling, mmWave, line-of-sight**

I. Introduction

The introduction of mmWave radio spectrum in 5G mobile systems presents a unique opportunity for the enhancement of mobile user experience through adoption of large channel bandwidths previously unattainable in conventional lower frequency cellular bands. Realisation of this opportunity however, presents significant deployment challenges resulting from the poorer in-building penetration, limited diffraction properties, and high susceptibility to blockage of mmWave bands relative to traditional cellular bands [1]. As such, mmWave deployment planning should be considered predominantly line-of-sight (LOS) dependent where service availability and the associated user experience can only be guaranteed in areas where clear LOS between transmitter and receiver is possible and where non-LOS/near-LOS contributes only opportunistic coverage. The same challenges exist in application of mmWave bands for more traditional deployment architectures such as backhaul transport solutions in urban environments, as such the LOS probability model is increasing relevance in use case analysis and deployment modelling of future dense network architectures.

A. Direct Line of Sight Use Cases

The LOS validation between transmit and receive points can be considered frequency independent (subject to the necessary Fresnel zone clearance requirements). Analytical prediction models such as those adopted by standards bodies including the ITU and 3GPP therefore hold value in a range of deployment scenarios aiming to utilise the bandwidths available in higher bands. The most noteworthy use case for operators is direct capacity uplift to existing mobile networks through addition of 5G FR2 bands (24-52GHz) [2] to existing cell site infrastructure. Other promising use cases include provision of multi-gigabit fixed wireless access (FWA) broadband services to surrounding premises and even support of new verticals such as ultra-reliable low latency communication (URLLC) vehicular connectivity. In all such applications the exploitation of existing cell masts offers the potential for significantly lower deployment cost over new-build street level cells.

In addition to the conventional mobile access applications, macro cellular sites also offer the potential as aggregation hubs for the backhaul transport network which could support onward densification of the radio access network (RAN) through proliferation of lower power street level small cells. It is envisaged that existing macro sites offer favourable edge node aggregation points for emerging ultra dense network architectures such as disaggregated or cloud RAN [3] and cell-free deployment models [4] where the required processing and resource management capability for a multitude (cluster) of cooperative cells can be coordinated. In this scenario the macro site may provide a (first hop) wireless connectivity solution to integrated access and backhaul (IAB) small cell nodes [5], where spectrum resources are shared or time sliced between access and backhaul transmissions. Alternatively, the optimal wireless transport solution may be provided by dedicated high frequency transmission bands such as E-band (71-86 GHz) [6], W-band (92-114.25 GHz) [7] or D-band (130-174.8 GHz) [8]. These fixed service bands promise a low latency high capacity wireless transport capability able to support fronthauling of lower layer functional split interfaces to new radio nodes [9]. Such a deployment topology would be logically more favourable from a capacity, latency and synchronisation perspective over traversing large scale fronthaul transport connections deeper into the network.

B. UMa Line-of-Sight Probability Models

For the urban macro cellular channel, a number of LOS probability models are recognised in standards and industry guidelines. The LOS probability model provides a means of

TABLE I: Urban Macro Line-of-Sight Probability Models.

Model	Definition	Parameters
3GPP UMa [10]	$Pr_{LOS} = \begin{cases} 1, d_{2D} \leq 18m \\ \left[\frac{d_1}{d_{2D}} + \exp\left(-\frac{d_{2D}}{d_2}\right)\left(1 - \frac{d_1}{d_{2D}}\right)\right]\left(1 + C'\left(h_{UT}\right)\frac{5}{4}\left(\frac{d_{2D}}{100}\right)^3 \exp\left(-\frac{d_{2D}}{150}\right)\right), 18m < d_{2D} \end{cases}$ $Where$ $C'^{(h_{UT})} = \begin{cases} 0, h_{UT} \leq 13m \\ \left(\frac{h_{UT}-13}{10}\right)^{1.5}, 13m < h_{UT} \leq 23m \end{cases}$ (1)	$d_1 = 18$ $d_2 = 63$
d_1/d_2 [11]	$Pr_{LOS} = \left(\min\left(\frac{d_1}{d_{2D}}, 1\right)\left(1 - \exp\left(-\frac{d_{2D}}{d_2}\right)\right) + \exp\left(-\frac{d_{2D}}{d_2}\right)\left(1 + C'\left(h_{UT}\right)\right)\right)$ (2)	$d_1 = 20$ $d_2 = 66$
NYU (Squared) [12]	$Pr_{LOS} = \left(\left(\min\left(\frac{d_1}{d_{2D}}, 1\right)\left(1 - \exp\left(-\frac{d_{2D}}{d_2}\right)\right) + \exp\left(-\frac{d_{2D}}{d_2}\right)\left(1 + C'\left(h_{UT}\right)\right)\right)\right)^2$ (3)	$d_1 = 20$ $d_2 = 160$

describing the likelihood of an endpoint Pr_{LOS}, generally considered to be mobile user equipment (UE), being in clear LOS of the base station as a function of the distance between them d_{2D}. The model definitions adopted into standards are typically evolutions of the same form and are based on stochastic approaches inherited from historic 2D models which inherently do not consider the relative environmental clutter dimensions [13]. A migration to 3D channel model extensions in 3GPP was first introduced in Release 12 with adoption of the ITU/WINNER II LOS probability model [14], [15]. The 3GPP LOS probability model was subsequently revised to account for the 3D end point height attributes h_{UT} [16] and later introduced in the form (1) into 3GPP TR 36.873 [17]. This revision was based on a ray tracing approach of a simulated urban city environment with uniformly distribution building heights between 15 and 25m, a compensation term $C\prime(h_{UT})$ was as included to account for inaccuracies in the base model above 13 m. More recently, revisions have been proposed to the UMa model underpinned by 5G mmWave channel characterisation including updated parametrisations in the 'd_1/d_2' model [11] in (2) and the addition of a squared term modifier in the 'NYU squared' model [12] in (3). These model definitions as well as the currently recognised 3GPP UMa LOS probability model are summarised in Table I.

The contributions presented in this study aim to qualify the suitability of frequency independent UMa 3D LOS probability channel models for large scale macro cellular network deployments. Section II outlines the experimental approach used to derive the LOS probability statistics and associated data sets in this study. Section III outlines the results of LOS analysis between real street furniture and real urban cell masts in selected towns and cities within the UK, these results are then evaluated against the aforementioned published models. Section IV proposes a new model based on analysis of theoretical endpoint heights of the same street furniture within the environmental model. Finally Section V summarises this work and direction of ongoing associated research.

II. Methodology

Each LOS validation in this study is calculated using a detailed 3D network topology and geographical topography environmental model built on high resolution LIDAR (Light Detecting and Ranging) data. Select areas of the UK are chosen as representative cities and towns covering approximately 1875 sq km including the large conurbations of London and Manchester and mid sized towns such as Sheffield, Salford and Rotherham. The model is constructed of publicly available LIDAR surveys from the UK Department for Environment, Food and Rural Affairs [18] of resolutions 0.25 m, 0.5 m and 1 m which are re-sampled into a single digital surface model (DSM) of resolution 0.25 m. The resultant DSM typically represents an order of magnitude greater resolution than the terrain data which would typically be used with conventional radio planning tools. Any 3D projections of the DSM are augmented with detailed terrain, building, road and green space datasets from Ordnance Survey [19] as well as BT/EE mobile infrastructure sites and lamp post locations in the area provided by local authorities under the UK Freedom of Information Act.

To align cell attribute definitions with those used in ITU and 3GPP, Voronoi polygons are constructed from site locations and the 2D inter-site distance (ISD) between each geometric neighbour calculated through construction of the associated Delaunay triangulation lines [20]. Only cells with an average ISD $\leq$500 m are classified and analysed as urban macro sites (UMa) in line with industry recognised definitions. LOS validation is carried out for over 20,000 lamp posts within the coverage area of 957 UMa cells for comparison with published urban LOS model predictions.

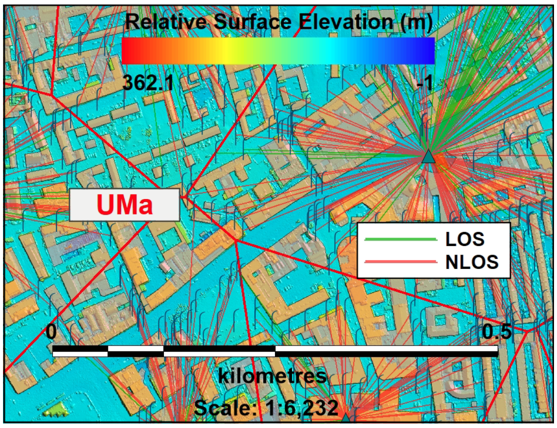

Fig. 1: Example DSM graphical representation.

A ray tracing approach is used where propagation lines are constructed between each macro site the lamp posts within it's Voronoi coverage area. The three dimensional propagation path between base station height and each corresponding lamp post height is recorded as LOS where no pixels are intersected by the underlying environmental model as shown in Fig. 1. The use of lamp posts as LOS endpoints in this study not only provides insight into the viability of using such street infrastructure for new radio head deployments which are wirelessly aggregated using mmWave technology to the nearest serving macro site (i.e macro hub backhaul aggregation or IAB donor node deployments), but they also act as a credible proxy for alternative UMa use cases. The lamp post locations and heights can be considered a reliable and representative geo-spatial sample point across the network environment for evaluation of alternative use cases such as those discussed in Section I. Small variation in the height or planar properties of the lamp post data points can be used to approximate mobile user equipment (UE) or vehicular terminals at a height of 1.5m on the adjacent pavement or road and FWA services to buildings at a height of 5m close to the pavement.

III. Street Furniture Case

A summary of the lamp post properties within the urban cells of the towns and cities studied are shown in Fig. 2 and Fig.3. The height distribution of lamp posts in Fig. 2 shows a discrete height profile distribution with the statistical mode being 6 m. It should also be noted that 99.9% of the data points under study are below 13 m in height. When considering the theoretical modelling of the lamp post data, the existing LOS probability models outlined in Table I would have no contribution from the height profile of this dataset as the $C\prime(h_{UT})$ height term remains zero below 13 m.

The relative distance of the lamp post data points to the serving macro sites in Fig. 3 follows a distribution with a positive skew where there are typically fewer points towards the cell edge. This is likely a result of both lamp posts and cell sites both being sited towards the centre of more densely populated areas.

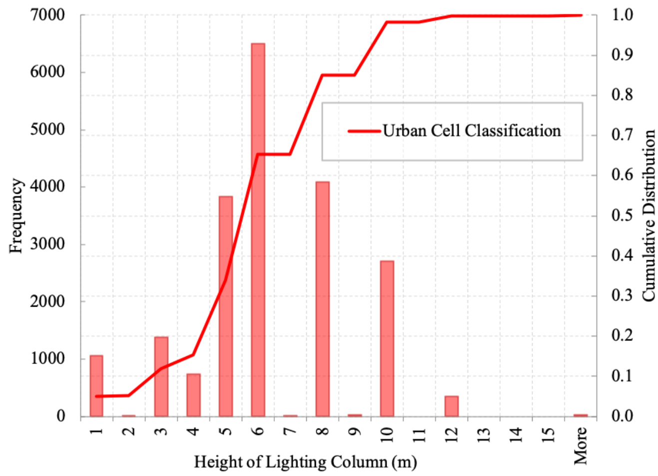

Fig. 2: Urban lamp post datapoint heights.

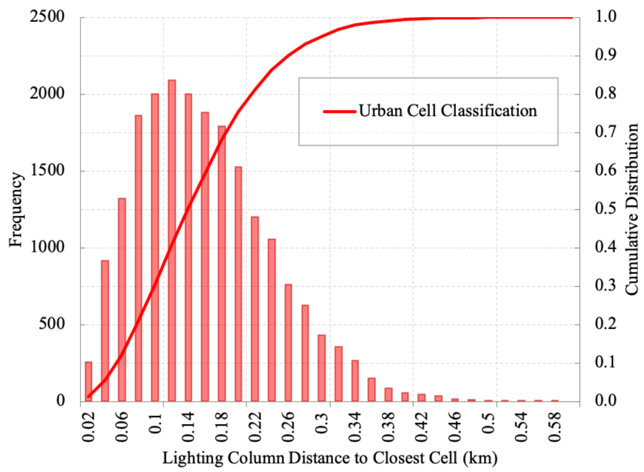

Fig. 3: Proximity of urban lamp posts to nearest cell.

The LOS probability results as a function of distance to the nearest cell site are outlined in Fig. 4. The default parameters for d_1 and d_2 together with optimised parameters through minimisation of the mean squared error (MSE) fitting between the results data and the UMa models in Table I are also overlaid in Fig. 4 and their suitability tabulated in Table II. In order to maintain statistical relevance for distances intervals with a lower number of data points as shown in Fig.3, a uniform data point count sampling approach is used across the cell radius as opposed to uniform distance sampling. In all cases, existing model definitions show poor agreement with the calculated data results which demonstrate a much lower LOS probability event towards the cell centre distances with a much flatter profile across the remaining cell radius. The considered models all show consistent over estimation of probability within a 150 m radius and significant under estimation beyond. In total, 22% of urban lamp posts within the towns and cities analysed could achieve LOS to their serving macro site.

TABLE II: Urban Macro Line-of-Sight Probability Models.

Model	Parameters		MSE
3GPP UMa [10]	Default	$d_1 = 18$ $d_2 = 63$	3.88
	Best Fit	$d_1 = 0$ $d_2 = 44$	0.54
d_1/d_2 [11]	Default	$d_1 = 20$ $d_2 = 66$	4.57
	Best Fit	$d_1 = 0$ $d_2 = 44$	0.54
NYU (Squared) [12]	Default	$d_1 = 20$ $d_2 = 160$	5.05
	Best Fit	$d_1 = 0$ $d_2 = 44$	0.54

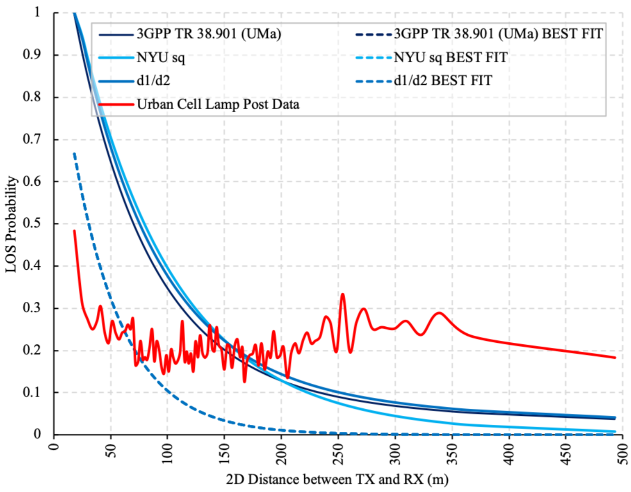

Fig. 4: LOS probabilty of urban lamp posts.

IV. Generalised Endpoint Height Case

The generalised LOS case to determine the influence of the endpoint height is achieved by reconfiguration the same lamp post dataset with modifications to the 3D height profiles. In the generalised case all the endpoint locations are reconfigured for a consistent height at increments between 1.5 and 10 m above ground level. The resulting LOS probability curve in Fig. 5 clearly highlights the significance of endpoint height properties below 13 m and the need for a model to account for such effects which are absent in existing models. A new model definition is consequently proposed in (4) and the resulting predictions overlaid in Fig. 5. The mean squared error results are summarised and the associated parameter optimisations defined in Table III. The 'BT UMa' model definition follows the 3GPP LOS model form with modified parametrisation and linear scaling variables $C\prime(h_{UT})$ and $D\prime(h_{UT})$ to account for end point height variation up to 10 m - the height considered by 3GPP for urban microcellular (UMi) deployments. The proposed model shows good agreement for all h_{UT} up to 10 m albeit with reduction in accuracy for cell edge probabilities as endpoint height increases. A common characteristic present in the results data is an increased probability / local maximum toward the cell centre. It is speculated that this is a charac-

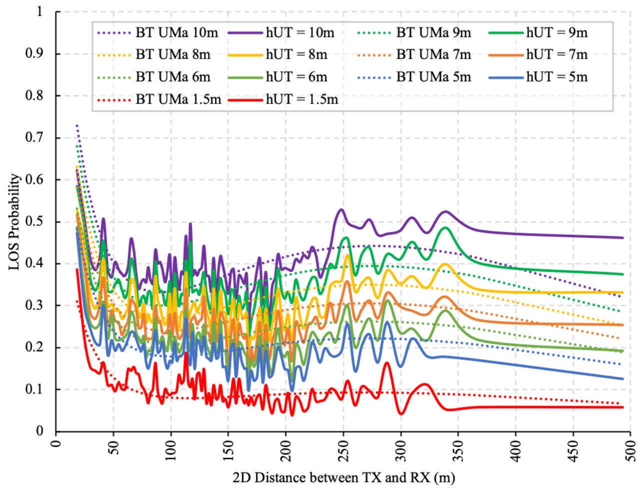

Fig. 5: Generalised height dependent LOS probability.

TABLE III: Parametrisation of BT UMa Probability Model.

Model	Parameters	Height	MSE
BT UMa	$d_1 = 3.69$ $d_2 = 5.47$ $c_1 = 0.013$ $c_2 = 0.38$	$h_{UT} = 1.5m$	0.07
		$h_{UT} = 5m$	0.08
		$h_{UT} = 6m$	0.09
		$h_{UT} = 7m$	0.10
		$h_{UT} = 8m$	0.13
		$h_{UT} = 9m$	0.52
		$h_{UT} = 10m$	0.19

teristic of the clutter environment where surrounding building height and density typically reduce with proximity to the cell site which is generally sited at the highest suitable location where demand and population are greatest.

$$
\begin{aligned}
Pr_{LOS} = & \left[\frac{D'\left(h_{UT}\right)}{d_{2D}} + \exp\left(-\frac{d_{2D}}{20}\right)\left(1 - \frac{D'\left(h_{UT}\right)}{d_{2D}}\right)\right] \\
& \times \left(0.4 + C'\left(h_{UT}\right)\frac{5}{4}\left(\frac{d_{2D}}{95}\right)^3 \exp\left(-\frac{d_{2D}}{150}\right)\right) \\
& Where \\
& C'\left(h_{UT}\right) = \left(c_1 h_{UT}\right) + c_2 \\
& D'\left(h_{UT}\right) = \left(d_1 h_{UT}\right) + d_2
\end{aligned} \tag{4}
$$

V. Conclusions

In this paper we utilise a large scale 3D environmental model built on high resolution LIDAR and infrastructure datasets to quantify the suitability of high frequency wireless systems when deployed on existing urban macrocell towers and rooftops. The derivation of the LOS probability distribution function in representative environments aims to support initial feasibility assessments of mmWave use cases. The findings presented in this paper have highlighted the unsuitability of established UMa LOS probability models for forecasting in a real network and geographical environment.

Fundamentally, the industry adopted models such as the 3GPP UMa LOS model are constructed using simulated city models where building height is uniformly distributed between 15 and 25 m [16] and base station locations and heights are assumed. Detailed mobile network and associated clutter characteristics of a live mobile network have previously been analysed by the authors preceding this contribution and re-enforce these assumptions to be poor approximations for a UK urban environment [20]. As a result, the published LOS probability models evaluated demonstrate a poor fit with the experimental dataset. In addition, the results highlight the significance of the terminal endpoint height at heights between 1.5 and 10 m above ground level when determining the likeihood of achieving clear LOS - a factor not currently addressed in recognised models. To address the gaps identified a new UMa LOS probability model is proposed which introduces greater flexibility in the user terminal height component and demonstrates a good fit to the underlying experimental data. Contributions outlined in this work intend to influence relevant industry simulation guidelines to further improve theoretical deployment modelling of mobile networks.

For the primary application under consideration, namely wireless transport aggregation hubs for small cell backhaul or IAB deployments, the results suggest the use of macrocells could be of value as a first hop transport link if onward wireless meshing to extend reach to a larger street level footprint is feasible. As such, further work looking at complimentary UMi LOS models for use in forecasting the viability of wireless links between potential lamp post sites (and radio nodes) is also under consideration.

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