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An Empirical Study of Urban Macro Propagation at 10, 18 and 28 GHz

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ABSTRACT

This paper investigates the propagation characteristics of the urban macro cells at centimeter-wave (cmWave) frequencies, in particular at 10, 18 and 28 GHz. The measurements are performed at several transmitter (Tx) locations and heights, in both line-of-sight (LOS) and non line-of-sight (NLOS) conditions, and with distances up to 1,400 m. The distance-dependent mean path loss and shadow fading standard deviation (std) are extracted for all cases based on a single-slope path loss model, and offered here for quick determination of link budget and system capacity. The results show the potential usage of the cmWave band for mobile cellular services in the years to come: the NLOS path loss slopes at 10 and 18 GHz are not much different from the 2 GHz reference, and the corresponding offsets are in the order of 20-23 dB for 25 m Tx height. This gap is expected to be overcome by the usage of high-gain miniaturized steerable antennas, which is feasible due to the reduced antenna aperture size at the cmWave band. Similar to the 2 GHz band, the NLOS shadow fading std for cmWave is within 6 dB. The effect of Tx height is clearly shown in the NLOS scenario: at 10 GHz, for example, 7.5 dB reduction in attenuation could be achieved by raising the Tx antenna from 15 m (below average roof-top) to 25 m (above roof-top), or 23.4 dB if the Tx height is elevated to 54 m.

I. INTRODUCTION

With the increasing demand for broadband wireless services, both academy and industry start eagerly looking into the future 5^{th} Generation (5G) wireless system, which envisions, among many other improvements, much higher bit rate over its predecessor. The current figure being discussed for the data rate requirement in 5G is 10 Gbps [1], which in turn requires a significantly larger available spectrum, i.e. hundreds of MHz or more. Therefore, the 5G system designers are looking above the usual 3 GHz spectrum, which is already crowded with radio, TV, mobile cellular, satellite, Global Positioning System (GPS), WiFi, etc.

The centimeter-wave (cmWave) band running from 3 to 30 GHz is one of the promising candidates for 5G, as it offers several GHz of available spectrum and has been largely unexplored for commercial wireless communications. So far this band has been mainly used for satellite communications, fixed wireless links, radar, defense and science applications. The Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society (METIS) identified several spectrum options above 6 GHz for 5G, namely 9.9-10.6 GHz, 17.1-17.3 GHz, 21.2-21.4 GHz and 27.5-29 GHz [2]. Even before deciding to open these bands up for cellular services, it is essential to gain a better understanding of their propagation characteristics and to establish simple channel models to evaluate the potential of such decisions.

To the best of our knowledge, there are only a handful of studies to model the urban outdoor path loss characteristics at these frequencies in the literature. Most of them, such as [3], [4], [5], target the fixed point-to-point or point-to-multi point wireless links, in which the receiver (Rx) is placed relatively higher than in the macro scenario. Other measurements, namely [6], [7], investigate the urban micro scenario, where Tx antennas are below the average roof-top. In [8] the 500MHz, 2, 5 and 15 GHz bands are measured in five Japanese cities, where the Tx antennas are well above or equal to the average building height. No path loss model is offered in the study, but the frequency-dependent path loss between frequency f_1 and f_2 is found to be $20log10(f_1/f_2)$ for both LOS and NLOS conditions. Reference [9] investigates the urban micro cell scenario at 28 GHz in New York University for 3 different Tx and 75 Rx locations over distances up to 500 meters, and similarly [10] measures one Tx and 30 different Rx locations in Daejeon, Korea. Although both studies provide insightful information on the multi-path characteristics at 28 GHz, the limited number of samples and the short measurement range make the extracted path loss model statistically less reliable.

At Aalborg University (AAU) we have carried out a set of measurement campaigns to characterize the performance of micro and macro deployments at the cmWave band. This paper addresses our latest empirical study on the potential usage of 10, 18 and 28 GHz bands for macro cells in an urban environment. The frequencies of interest are chosen so as not only to cover the spectrum opportunities identified by the METIS, but also to complement other AAU measurements below 6 GHz and to evenly spread across the cmWave band with the aim of collecting an overall understanding of this spectrum. Such knowledge is essential for the research community to come up with a unified path loss model that works across all frequency bands, from below 3 GHz to millimeter-wave (mmWave) band. All frequencies are measured with reference to the well-known

Fig. 1. Measurement locations in a residential area of Aalborg, Denmark.

TABLE I
FREQUENCIES AND MEASURED ROUTES

Frequency	Tx Height	Location(s)	Meas. Range	# Samples
10 GHz	15 m	2, 3	54.5 - 793.5 m	8,765
	20 m	1a	60.5 - 880.3 m	3,022
	25 m	2, 3	60.2 - 1239.3 m	19,723
	54 m	4a, 4b	68.4 - 1425.5 m	28,123
18 GHz	15 m	3	52.8 - 926.8 m	5,296
	20 m	1a	60.2 - 870.6 m	3,328
	25 m	2, 3	60.8 - 1032.3 m	10,285
	54 m	4a, 4b	52.2 - 1429.1 m	31,064
28 GHz	15 m	1b, 3	50.7 - 539.8 m	5,841
	20 m	1a, 1b	60.4 - 539.8 m	3,328
	25 m	1b, 2, 3	50.7 - 876.7 m	10,285

2 GHz in the same environment to establish the path loss differences between them. The effect of Tx height is also investigated. We propose single-slope path loss models for a set of cases, which facilitates the determination of coverage distances, system capacity and link budgets for viable links in futuristic cellular systems. The proposed models benefit from the fact that our study has a longer range and more data samples than the previous works, hence with higher reliability and confidence.

The rest of the paper is organized as follows: In Section II we describe the measurement setup and applied calibration procedure to ensure meaningful results are obtained. Section III discusses our findings separately for the LOS and NLOS scenarios, and finally the conclusions are given in Section IV.

II. Measurement scenario and setup

To study the urban macro's propagation characteristics at the cmWave band, a drive-test measurement campaign was carried out between March and July 2015 in Aalborg, Denmark. This experimental area represents a typical medium European city's residential district, in which the building height and street width are relatively homogeneous and measured at 17 and 20 meters, respectively. The measurement setup consists of a stationary Tx and a Rx mounted on a moving van. Figure 1 shows six locations of the Tx carefully chosen to cover the experimental area. At locations 1a, 1b, 2, and 3, the Tx is elevated to different heights by the usage of a boom lift, while at locations 4a and 4b, it is placed on top of a tall hospital building. The combinations of frequency, Tx height, location, measured range (minimum and maximum Tx-Rx separation) and number of measured samples are given in Table I.

At the Tx, a narrowband continuous wave (CW) signal with the carrier frequency of interest, i.e. 10, 18 and 28 GHz, is fed to the Tx antenna with 35-39 dBm output power, depending on the frequency. Each frequency uses a separate horn antenna, but they all have similar characteristics of 55^o half-power beamwidth (HPBW) in both the elevation and azimuth planes and 10 dBi maximum gain. No tilting is applied, except for the location 4a and 4b, where 11^o mechanical down-tilt is added to ensure that the elevation HPBW of the Tx antenna covers the entire experimental area. Another narrowband CW signal at 2 GHz is always transmitted and recorded in parallel to serve as a reference. The 2 GHz band horn antenna is slightly wider, i.e. 60^o HPBW in both planes, and has lower maximum gain of 7 dBi. The output power for this branch is 36 dBm.

The Rx is placed on a van, which is driven around in the experimental area at an average speed of 20 km/h. The driving routes are chosen so that they are confined within the HPBW of the Tx antennas. Two Rx antennas are mounted on top of the van, which is 2.5 m high. One dipole antenna is used at 2 GHz, while another biconical antenna is used for all other frequencies. The dipole has 2 dBi maximum gain and 35^o HPBW in elevation, while the biconical antenna typically has 0 dBi gain and 45^o, 20^o and 20^o elevation HPBW at 10, 18 and 28 GHz, respectively. The received signal strength and GPS location are recorded at rate of 10 samples/s using the R&S TSMW Universal Radio Network Analyzer for extracting the corresponding path loss and 3-dimension (3D) Tx-Rx separation later. The measurement points are visually identified as LOS and NLOS on Google Maps during the post-processing stage. It is worth noticing that there are almost line-of-sight (ALOS) points, e.g. the LOS direction is partially blocked by building corners or trees, present in both LOS and NLOS data sets.

$$\begin{aligned} L[dB] =& P_{Tx}[dBm] - P_{Rx}[dBm] \\ &- L_c[dB] + G_{Tx}[dB] + G_{Rx}[dB] \end{aligned} \tag{1}$$

The path loss L is computed using Eq. (1), where L_c is the total cable loss at both sides, which is a constant for each frequency. P_{Tx}, P_{Rx}, G_{Tx} and G_{Rx} are the transmitting and receiving powers and antenna gain, respectively. It is important that the antenna gains are correctly decoupled from the path loss, otherwise it is going to cause bias to the extracted path loss model. In our study we assume that the Tx antenna gain is equal to the maximum, because the measurement routes are confined within the HPBW of the Tx antenna. On the other hand, the Rx antenna gain is assumed to depend only on the elevation Angle of Arrival (AoA), since it is relatively omni-directional in the azimuth plane. This elevation AoA is calculated geometrically based on the positions of Tx and Rx, assuming that they are in LOS.

To verify the above-mentioned antenna pattern decoupling

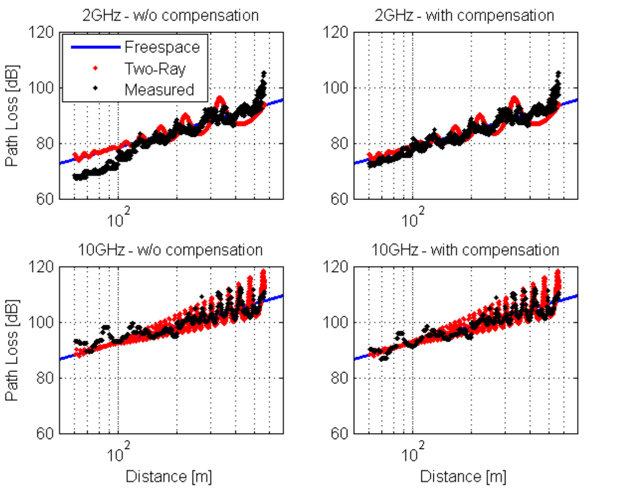

Fig. 2. Measured path loss from the location 1a before and after compensating for the Rx elevation pattern.

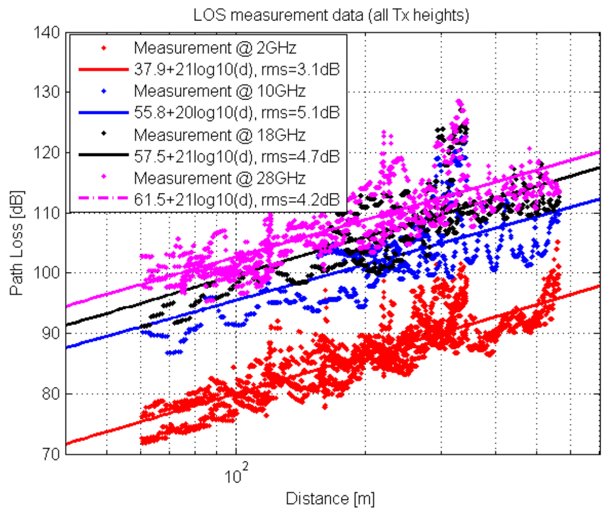

Fig. 3. Measured path loss data and models in the LOS scenario (all Tx heights).

approach, we measure the path loss on a clear and straight LOS route, with virtually no buildings along the road to avoid additional reflections and/or diffractions. Figure 2 shows the path loss measured at location 1a before and after antenna pattern compensation at 2 and 10 GHz. It is clear that without compensation the path loss will be under-estimated at close range, especially for the 2 GHz band. The compensated path loss data match well both free-space and two-ray (or ground reflection) path loss models, which is expected for such a clear LOS scenario [11]. The root mean square (rms) errors before and after compensation between measurement and two-ray model for the 2 GHz band are 4.2dB and 3.8dB, respectively.

III. Result Analysis

In this section we look at the measurement data after they have been classified into LOS and NLOS conditions. To extract the distance-dependent mean path loss, a single-slope path loss mode called Alpha-Beta (AB) model is applied [14]:

$$PL(d)[dB] = \alpha + \beta \times 10\log_{10}(d[m]) \tag{2}$$

where $PL(d)$ in dB is the mean path loss over the Tx-Rx separation d (in meters), α is the floating intercept in dB, and β is the average path loss exponent. The path loss exponent (or slope) and the floating intercept can be derived using a least-square linear regression fit from the set of measurement data as follows:

$$\beta = \frac{\sum_{i=1}^{N}(D_i - \bar{D})(L_i - \bar{L})}{\sum_{i=1}^{N}(D_i - \bar{D})^2} \tag{3}$$

$$\alpha = \bar{L} - \beta \times \bar{D} \tag{4}$$

where L_i is the path loss value and $D_i = 10\log_{10}(d_i[m])$ is the Tx-Rx separation distance in dB scale of the i^{th} measurement point ($i = 1, 2, ...N$). $\bar{L} = \frac{1}{N}\sum_{i=1}^{N} L_i$ and $\bar{D} = \frac{1}{N}\sum_{i=1}^{N} D_i$ is the average path loss and average distance of the entire data set, respectively. The rms error between the measurement data and the mean path loss is also computed and shown here, because it serves two purposes: first, it is an indication of how well a model fit with the measurement data, and secondly it represents the path loss fluctuation due to obstacles and other random propagation effects, which is useful for establishing the shadow fading model. The shadow fading is often modeled as log-normal distribution with zero mean and standard deviation equivalent to the rms error.

TABLE II
Path Loss models for LOS scenario

Frequency	AB Model			Free-space	Offset
	α	β	rms error	rms error	
2 GHz	37.9	2.1	3.1 dB	3.8 dB	0.0 dB
10 GHz	55.8	2.0	5.1 dB	5.9 dB	14.3 dB
18 GHz	57.5	2.1	4.7 dB	5.4 dB	19.2 dB
28 GHz	61.5	2.1	4.2 dB	4.9 dB	22.4 dB

A. LOS path loss

The LOS data with different Tx heights are collectively analyzed, because there is no indication that they depend on the Tx height, but only on the 3D distance between Tx and Rx. Figure 3 shows the data set as a function of the 3D distance, and also the corresponding mean path loss model for each frequency band. At cmWave, the mean path loss tends to increase with a rate of 20 dB per decade, which is very similar to the 2 GHz. Alternatively, one can use the free-space path loss [11] to describe the mean path loss for cmWave in LOS scenario at the expense of slightly increased rms error. Table II summarizes the rms error for both AB and free-space path loss models, and the maximum difference between them is 0.8 dB at 10 GHz. Based on our observations, the cmWave signal faces more severe attenuation in ALOS conditions than the 2 GHz band, and that contributes to an increase in shadowing variability.

It is of our interest to compute the mean offset between the path loss of the cmWave and reference bands, as it

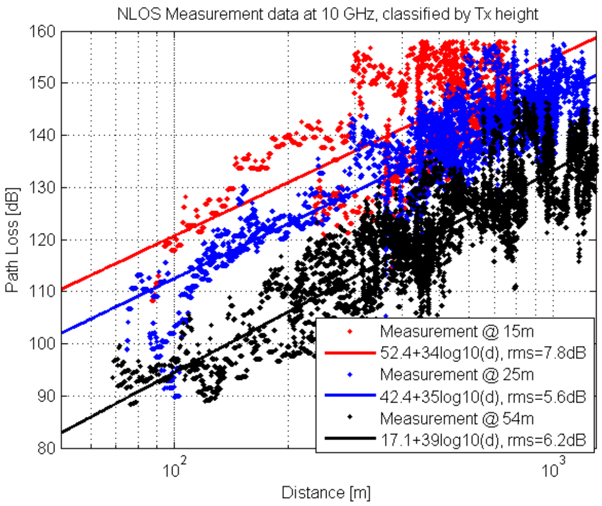

Fig. 4. Measured path loss data for the 10 GHz band at different Tx heights.

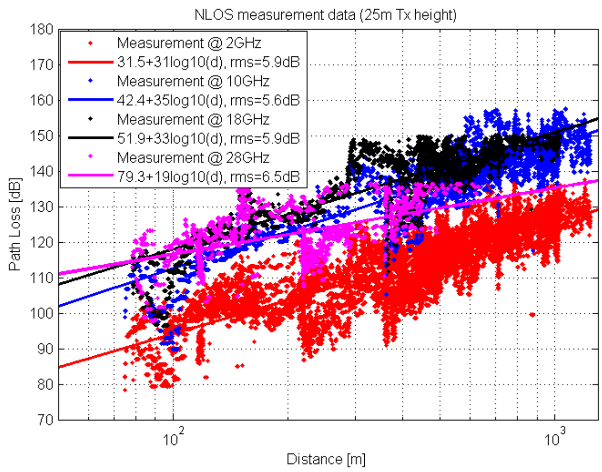

Fig. 5. Measured path loss data and models in the NLOS scenario (Tx at 25 m height).

is an indication of how much worse the former performs compared to the later. To this end, the measurement points are sorted into bins with a 50 m step size based on the 3D distance, and then averaged at each bin to remove the effect of fast and shadowing fading. The averaged path loss values at the frequencies of interest are subtracted bin-by-bin from counterparts at 2 GHz, and then averaged over all bins to obtain the mean path loss offsets in Table II. In line with the findings in [8], the frequency-dependent offset for LOS is found to be approximately $20log10(f_1/f_2)$, where $f_1 = 10, 18, 28$ and $f_2 = 2$.

B. NLOS path loss

Unlike the LOS scenario, the Tx height has a significant impact on the path loss for NLOS. Figure 4 plots the measured NLOS path loss at 10 GHz across 15, 25 and 54 m heights. The path loss reduces with increasing Tx height as expected, since this helps to reduce the number of obstacles before reaching the Rx, as well as the diffraction loss when the signal propagates over-the-roof-top. The offset between mean path loss at the Tx height of 15 and 25 m is approximately 7.5 dB, while between 15 and 54 m is 23.4 dB, which is a significant increase with the reduction of Tx height. This trend happens at all frequency bands in our measurement campaign, even though the Tx height gain values are not the same (see Table III).

Table IV gives the AB model's parameters and rms errors for all frequency and height combinations. For a Tx height of 25 meter, which is above the average roof top, the path loss exponent ranges from 3.3 to 3.5 for the cmWave band, except for 28 GHz band. This is slightly higher than the 2 GHz band

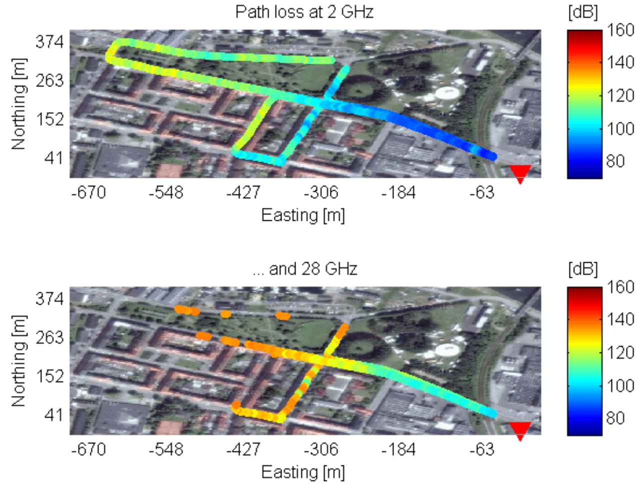

Fig. 6. Measured path loss at the Tx location 3 for the 2 and 28 GHz bands.

TABLE III
OFFSET DUE TO TX HEIGHT IN NLOS SCENARIO

Frequency	**Offset (dB)**		
	15 vs 25 m	25 vs 54 m	15 vs 54 m
2 GHz	4.0	11.8	15.7
10 GHz	7.5	14.8	23.4
18 GHz	*Not available*	14.2	*Not available*

TABLE IV
PATH LOSS MODELS FOR NLOS SCENARIO

Frequency	**Tx Height**	**AB Model**			**Offset**
		α	β	rms error	
2 GHz	15 m	14.4	3.9	8.0 dB	0.0 dB
	25 m	31.5	3.1	5.9 dB	0.0 dB
	54 m	18.0	3.2	5.4 dB	0.0 dB
10 GHz	15 m	52.5	3.4	7.8 dB	24.0 dB
	25 m	42.4	3.5	5.6 dB	20.3 dB
	54 m	17.1	3.9	6.2 dB	17.6 dB
18 GHz	*15 m*	*6.0*	*4.9*	*4.5 dB*	*18.7 dB*
	25 m	51.9	3.3	5.9 dB	23.9 dB
	54 m	25.3	3.7	6.0 dB	21.5 dB
28 GHz	*15 m*	*63.8*	*2.5*	*6.4 dB*	*13.8 dB*
	25 m	*79.3*	*1.9*	*6.5 dB*	*19.1 dB*

at the same height, where the slope is 3.1. Figure 6 shows the path loss data at 2 and 28 GHz in the same drive-test route: the 28 GHz path loss becomes too high when the Rx is completely behind obstacles; in those cases the receiver sensitivity is reached and therefore no measurement is possible. This is coherent with the findings in [3]. In Table IV we marked in *italic* the frequency and height combinations, in which a large portion of the path loss data exceeds the receiver's sensitivity. The path loss models extracted from these data sets might be less representative than the others, but they are presented anyway here for the sake of completeness. They also indicate that the cell range for the 18 GHz band will be limited if the Tx is placed below average roof-top, and the 28 GHz tends to work only in LOS and ALOS conditions, unless the excessive path loss is compensated by higher transmitter powers or high-gain antennas.

Unlike in the LOS scenario, our observation shows no significant evidence that the NLOS shadowing variability is frequency-dependent. Considering only credible data sets from Table IV, the rms errors range from 5.4 to 6.2 dB for the Tx above average roof-top (i.e. at 25 and 54 m), which is well-aligned with the urban macro shadow fading standard deviation (std) of 6 dB specified in 3GPP [12]. Nevertheless, the measured path loss tends to spread more around its mean for the Tx height below average roof-top, probably due to the fact that more diffractions, reflections or scatterings are needed for the signal to reach the Rx in this case.

The NLOS mean path loss offsets between cmWave and the 2 GHz reference at the corresponding Tx height are given in Table IV. The offset increases for the NLOS scenario compared to the LOS case, and tends to reduce with the increase of Tx height. For example the offset between 10 and 2 GHz starts at 14.3 dB for LOS, and increases to 17.6 dB for NLOS with Tx height of 54 m, and then to 23.9 dB with Tx is below average roof-top. Such an offset increase can be explained by the fact that the diffraction loss tends to increase by 3 dB when the frequency is doubled [13], and also the number of obstacles increases when lowering the Tx height, and so does the number of diffractions along the path.

IV. Conclusions

This paper presented the measurement campaign for urban macro cells at 10, 18 and 28 GHz in Aalborg, Denmark. Four different Tx heights are measured at 6 locations, and the maximum Tx-Rx separation is greater than 1,400 meter. The measurement data are classified into LOS and NLOS conditions, and analyzed separately. For the LOS scenario there is no indication that the path loss depends on the Tx height, but only on the increase of the Tx-Rx separation. The LOS path loss tends to increase with a rate of 20 dB per decade for all measured frequencies. In the NLOS conditions, the Tx height shows significant impact on the path loss. For example raising the Tx height from 15 m (below average roof top) to 25 m (above roof top) could result in 7.5 dB gain at 10 GHz, and from 25 m to 54 m could bring another 14.8 dB. The NLOS path loss exponent for the cmWave frequencies (excluding the 28 GHz band) ranges from 3.3 to 3.5, which is only slightly higher than that of 2 GHz band. While in LOS the frequency-dependent offset follows $20log10(f_1/f2)$, it is larger in the NLOS scenario and also depends significantly on the Tx height. For example the offset between 10 and 2 GHz goes from 14.3 dB for LOS to 17.6 dB for NLOS with Tx height of 54 m, and then to 23.9 dB at 15 m Tx height. The cmWave exhibits similar NLOS shadow fading variability compared to that of the 2 GHz reference, i.e. the std remains at around 6 dB for all measured frequencies bands.

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