Abstract—Maximization of 5G millimeter-wave base station coverage and range is important to reduce the number of required base stations. Buildings could be used as reflectors to provide coverage in NLOS areas due to their high reflectivity at millimeter-waves. This paper presents the results of a measurement campaign investigating specular reflections from buildings at 24.00-24.25 GHz. The angle of minimum path loss for single-building reflections agrees well with the direction of the specular path. This agreement is less accurate in case of a double-building reflection, possibly due to obstructions in the specular path or multipath fading. In case of a single-building reflection, 1-9 dB excess loss compared to free-space path loss is measured. The excess loss is in the range of 9-20 dB for a double-building reflection. Although more research on this topic is required, these results are promising and indicate that buildings can be used as effective millimeter-wave reflectors.

Index Terms—5G, measurements, millimeter-wave, propagation, reflection.

I. INTRODUCTION

The large bandwidth available in the millimeter-wave (mm-wave) band can be used for high capacity and high data-rate applications in 5G. The n257 and n258 5G New Radio (NR) bands are defined at the lower end of the mm-wave spectrum between 24.25-29.50 GHz [1]. The higher propagation loss in the mm-wave band compared to the 4G frequency range below 6 GHz requires smaller cell sizes for 5G mm-wave. Providing complete coverage in Urban Macro (UMa) and even Urban Micro (UMi) cells with inter-site distance (ISD) of typically 500 m and 200 m [2], [3], respectively, is very challenging at mm-wave. 5G mm-wave early deployment will target high capacity applications, like stadiums and open squares (OS). The coverage range of a base station at an OS might be extended by using buildings to effectively reflect the signal towards non line-of-sight (NLOS) areas.

The mm-wave reflectivity of buildings and building materials has been investigated in the past. In [4], a reflection coefficient of 0.896 at 28 GHz for an incident angle of 10° is reported for tinted glass. This is equivalent to a reflection loss of only 1 dB. In addition, reflection coefficients for concrete of 0.815 and 0.623 for 10° and 45° incident angle, respectively, are reported in [4], which are equivalent to a reflection loss of 2 and 4 dB, respectively. Building reflection loss at normal incidence relative to free space path loss (FSPL) at 28.8 GHz is investigated in [5]. Reflection losses up to 8 dB are reported for metal building surfaces. The reflection loss for brick and concrete surfaces range from 7-15 dB. So especially glass and metal surfaces of buildings are potentially effective mm-wave reflectors. In this paper, specular reflections from two buildings with surfaces that mainly consist of these materials are investigated.

This paper is organized as follows. In Section II, the measurement system and parameters are discussed. The measurement scenario is described in Section III. In Section IV, the measurement results are presented and described. Finally, conclusions are drawn in Section V.

II. MEASUREMENT SYSTEM AND PARAMETERS

A. Measurement System

A block diagram of the measurement setup is depicted in Fig. 1. At the transmitter (Tx), a 0 dBm continuous-wave (CW) signal of 24.000, 24.125 and 24.250 GHz is generated sequentially by an HP8350B sweep oscillator. This signal is amplified by a 20 dB power amplifier (PA) [6]. The signal power is measured with a FieldFox N9918A spectrum analyzer at the receiver (Rx) after amplification by a 23 dB low-noise amplifier (LNA) [7]. The Tx and Rx antennas are identical 17 dBi standard gain horn antennas (SGHs) with a half-power beamwidth (HPBW) of 24.2° in the H-plane and 24.6° in the E-plane [8]. Vertical antenna polarizations are used during the experiments.

A tracking algorithm is created to track the relative frequency drift between the Tx and Rx, and to enable measurements with a 25 kHz span to decrease the measurement time and increase the measurement accuracy. The measurement accuracy is further improved by measuring 10 snapshots. A lower bound of -75 dBm of measured power on the spectrum analyzer is used, which is approximately 10 dB above the noise floor. This results in an upper bound on the path loss.
(PL) of approximately 137, 138 and 139 dB for the frequencies 24,000, 24,125 and 24,250 GHz, respectively.

The Rx antenna is rotated 360° in 9° steps in the horizontal $\phi$-plane by a motorized rotation platform, which is depicted in Fig. 2. The position of the rotation platform with respect to the cart is determined using a Hall sensor. The orientation of the cart with respect to True North is determined with a compass including a compensation for the declination angle. An initialization stage is used during the measurements to align the 0° Rx pointing angle $\phi$ to True North. The measurement time per frequency is 8 s. Measurement of the three frequencies and rotation to the next angle $\phi$ takes 30 s. The total measurement time over all 40 Rx pointing angles $\phi$ is 20 min.

The measurement system is calibrated via an over-the-air (OTA) calibration as described in [9]. The calibration is performed at reduced Tx power to prevent saturation of the LNA. A small compensation for the different response of the PA is applied to account for its non-linearity.

### B. Measurement Parameters

The PL in dB can be calculated as

$$PL(f, \phi) = P_{\text{cal}}(f) - \frac{1}{N(f, \phi)} \sum_{n=1}^{N(f, \phi)} P_{\text{meas}}(f, \phi, n)$$  \hspace{1cm} (1)

where $P_{\text{cal}}(f)$ is a calibration term, $P_{\text{meas}}(f, \phi, n)$ is the measured power at frequency $f$, Rx pointing angle $\phi$ and snapshot $n$ and $N(f, \phi)$ is the number of snapshots above the lower bound of -75 dBm for the received power. The mean PL as function of $\phi$ can be calculated as

$$\bar{PL}(\phi) = \langle PL(f, \phi) \rangle_f ,$$  \hspace{1cm} (2)

where $\langle \cdot \rangle_f$ denotes the mean over frequency. The minimum PL is defined as

$$PL_{\text{min}} = \min\{PL(\phi)\} = PL(\phi_{\text{min}})$$  \hspace{1cm} (3)

where $\phi_{\text{min}}$ denotes the Rx pointing angle at which the mean PL over frequency is minimum. The PL calculated in (1) is the magnitude of the complex sum of all measured paths. No temporal distinction between multiple paths can be made with this measurement setup. However, the likelihood of fading is reduced by using directional antennas. Moreover, the PL at the three measured frequencies can be compared to indicate the likelihood of fading affecting the results.

The antenna pattern is not de-embedded from the measurement results. The underestimation of $PL_{\text{min}}$ due to misalignment of the angle-of-arrival (AOA) and the Rx antenna pattern peak in the H-plane is maximally 0.5 dB. For the misalignment of the Tx antenna pattern peak and the angle-of-departure (AOD), the underestimation is maximally 0.2 dB due to the small field of view of the Tx antenna, which is shown in Section III. These underestimations are neglected here. Antenna pattern de-embedding could improve the accuracy of the AOA estimation and is needed to accurately determine the omni-directional PL. Antenna pattern de-embedding will be included in future work.

### III. Measurement Scenario

Measurements to investigate building reflections to provide extended coverage to NLOS areas are conducted in a parking lot of the Eindhoven University of Technology campus in Eindhoven, the Netherlands. Fig. 3 depicts a modified map of this area generated with Google Earth Pro. Three buildings are labeled B1, B2 and B3. The building outlines at ground level are marked in yellow. The picture is taken at a small angle, so these outlines do not fully coincide with the depicted buildings. The Tx antenna is placed at a balcony of B1 at a height of 17 m. This balcony is faced towards a 12 000 m$^2$ OS. The Tx antenna is pointed towards the middle of B2. The part of B2 that is visible from the Tx location is well within the HPBW of the Tx antenna. The six Rx locations are labeled Rx 1-6. The Rx antenna height is 1.5 m. No direct LOS link between the Tx and Rx locations is possible due to blockage...
The most likely possible obstructions are the trees in front of B2 and B3, and the pedestrian bridge between B1 and B2. The trees around Rx 3-5 are so tall that only their trunks could cause blockage. Fig. 5 shows the vertical cut of the environment spanning the specular paths between the Tx and Rx 1, 4 and 6. The effect of the slightly different path of Rx 1 in the horizontal plane compared to Rx 4 and 6 is negligible and thus neglected here. The Tx, Rx and building locations are depicted, as well as the pedestrian bridge and the trees in front of B2. The height range of the square flat surface of B2 is depicted in blue in Fig. 5. The paths between the Tx and Rx locations are drawn assuming also specular reflections in the vertical plane. The vertical cut shows that a reduction in PL could be expected at Rx 1 due to possible blockage of the specular path by the bridge and the trees, and since the specular path does not intersect with the flat surface at B2. For Rx 4 and 6, there is no blockage expected from the bridge and the trees. Moreover, their specular paths intersect with the square flat surface of B2. The specular paths of Rx 4 and 6 do not show any influence of obstructions. However, there are three trees in front of B3 that are close to the specular path of Rx 4. There is a tree in the specular path of Rx 5, as can be seen in Fig. 3.

IV. Measurement Results

The measurement results are discussed in this section. In Section IV-A, the measured PL is presented and evaluated for all Rx locations. The likelihood of multipath fading in the presented results is analyzed and discussed in Section IV-B. In Section IV-C, the minimum measured PL is compared to FSPL.

A. Measured PL

Fig. 6 depicts $PL(\phi)$, the mean PL over frequency as function of Rx pointing angle $\phi$, calculated using (1) and (2). Fig. 7 displays this data on a map. There is no value...
Fig. 7. Spatial representation of $\text{PL}(\phi)$.

displayed for some angles $\phi$ of the Rx locations. This means that there is no snapshot with a measured power above the lower bound of -75 dBm in these cases. The main lobe of the antenna pattern is clearly visible in the results. For every Rx location, there is only one dominant direction in which $\text{PL}(\phi)$ is lowest. Rx 1, 2 and 6 indicate a path via a single reflection from B2. The minimum PL is obtained via a double reflection from B2 and B3 for Rx 3-5. For Rx 1 and 6, $\phi_{\text{min}}$ matches the direction of the specular paths well. In case of Rx 3 and 4, there is a mismatch in the order of an angular step of 9° between $\phi_{\text{min}}$ and the specular paths. The specular paths are within the HPBW of the Rx antenna at $\phi_{\text{min}}$ for Rx 3 and 4. So the mismatch could be explained by multipath fading, which is discussed in Section IV-B. A different cause could be blockage by trees in or close to the specular paths. The mismatch is in the range of 20°-25° for Rx 5. This could be due to the fact that the specular path of Rx 5 is at the estimated boundary of the red zone in Fig. 3. This predicted specular path is also close to the edge of the building where a tree is in the specular path. At Rx 2, where no specular path is possible, the minimum PL, $\text{PL}_{\text{min}}$, is highest. $\text{PL}_{\text{min}}$ is 19 dB larger than at Rx 1, which is a nearby location within the specular path. The smaller $\text{PL}_{\text{min}}$ at Rx 1 compared to Rx 6 could be explained by blockage from the obstructions discussed in Section III-A.

B. Likelihood of multipath fading

A comparison of the PL at the different frequencies gives insight into the likelihood of multipath fading. Fig. 8 depicts $\text{PL}(f, \phi_{\text{min}})$ and $\Delta \text{PL}_{\text{max}}$, the maximum variation in PL over frequency at $\phi_{\text{min}}$. $\Delta \text{PL}_{\text{max}}$ is less than 1 dB for Rx 1 and 6, which suggests no significant multipath fading in these measurements, where a strong specular component is present. $\Delta \text{PL}_{\text{max}}$ is 7 dB at Rx 2. Only a small part of this fluctuation in PL can be imputed to fluctuation due to noise. Monte Carlo simulations of a signal plus noise model, using the measured noise floor distribution and 100k Monte Carlo runs namely show a worst case variation of 2.5 dB for a PL of 133 dB. For Rx 3-5, $\Delta \text{PL}_{\text{max}}$ is between 3 and 6 dB. In [10], the effect of small-scale fading is investigated by moving an Rx over a ten wavelengths long track at an interval of a half wavelength. A 6 dB fading variation of the main peak in the power delay profile (PDP) is reported there and indicated as having little influence on the AOA and received power level of multipath signals. Although no direct comparison can be made between power variation in a PDP and in frequency domain, this shows that such variation in measured PL can also be expected in wideband channel measurements. Measuring more frequency points in a wider frequency band would improve the fading detection. In this work, the effect of multipath fading is reduced by averaging over frequency.

Fig. 8. Variation in PL at $\phi_{\text{min}}$ between the measured frequencies.

Fig. 9. Minimum mean PL compared to FSPL corresponding to the specular paths as displayed in Fig. 3.
C. Comparison of measured $PL_{\text{min}}$ and FSPL

Fig. 9 displays $PL_{\text{min}}$ and the FSPL for a path length corresponding to the specular path of Rx 1 and 3-6, where the FSPL is averaged over frequency. In case of Rx 2, where no specular path is present, the path via $\phi_{\text{min}}$ is used to determine the path length. The estimated path lengths are 148, 154, 284, 290, 297 and 216 m for Rx 1-6, respectively. The excess loss at Rx 6 is less than 1 dB, which indicates that a building like B2 can be a very good specular reflector. The excess loss for Rx 1 is 9 dB. This larger excess loss compared to Rx 6 could be due to blockage by the obstructions in front of B2 and because the specular path does not intersect with the square flat surface of B2. Only 9 dB excess loss is measured at Rx 4 for a double specular reflection. It cannot be conclusively determined which parts of this loss are due to reflection loss, fading and blockage by obstructions. The excess loss of 28 dB at Rx 2 suggests that the lack of a specular path significantly increases the PL. This observation is supported by the relatively large PL for $\phi$ pointing towards B2 at Rx 3-5 as can be seen in Fig. 7.

V. CONCLUSIONS

The possibility to provide NLOS coverage using specular building reflections is investigated in this paper. Paths via single- and double-building reflections are obtained at the corresponding Rx locations according to the prediction based on specular reflections. In case of a single-building reflection, 1-9 dB excess loss compared to FSPL is found. The excess loss ranges from 9-20 dB in case of a double-building reflection. There is a good agreement between the specular path and the angle of minimum PL for single-building reflections. This agreement is less precise in case of a double-building reflection with a rough difference of 9°-25°. This could be due to blockage by obstructions and/or multipath fading in the measurements. An excess loss of 28 dB is measured for a single reflection without a specular path. These results support the hypothesis that buildings could be used as efficient mm-wave reflectors to increase the coverage in NLOS areas. However, more measurements are required to obtain accurate average excess losses for single- and double-building reflections, and to be able to distinguish between reflection loss and loss due to blockage. Furthermore, investigation of different incident angles and other building surfaces is important to show the feasibility of NLOS coverage using specular building reflections in different environments.

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REFERENCES