Abstract—This paper presents coverage and penetration loss measurements in an urban environment at 15 GHz to provide insight into the design and deployment of future 5G systems in higher frequency bands. The measurements are performed using a 5G radio access prototype including two transmission points (TPs) and a mobile terminal over a 200 MHz bandwidth. The TPs and the mobile terminal each consists of multiple antennas, enabling spatial multiplexing of multiple data streams. Coverage measurements are performed for both outdoor and outdoor-to-indoor scenarios. Penetration losses are measured for human body, normal and coated windows, a metallic white board, and a concrete pillar. Outdoor microcellular coverage in line-of-sight (LOS) and lightly shadowed areas is shown to be possible with similar antenna directivities as in the existing cellular networks. Transitions into non-line-of-sight (NLOS) bring additional losses in the order of 20 dB, thereby making the NLOS coverage challenging. Outdoor-to-indoor coverage seems to be limited to areas that are in almost LOS with the outdoor TP. Moreover, the penetration loss of indoor blocking objects seems to further restrict the indoor coverage. Potential of beamforming as a means to improve the coverage are also evaluated via simulations.

Keywords- 15 GHz, 5G, Coverage, Propagation, Prototype

I. INTRODUCTION

The next generation of cellular networks, 5G, will target radically improved capacities and peak data rates compared to those achievable in current networks. Substantially larger bandwidths are foreseen to be needed to meet these requirements. One way to access such large bandwidths is to exploit the rather idle spectrum at higher frequencies, up to and including millimeter wave frequencies [1-2]. In addition, due to the smaller wavelength at higher frequencies, many of the state-of-the-art multiple-antenna technologies, such as spatial beamforming, spatial multiplexing, etc., can be implemented using antennas with smaller form factors [3]. Hence, currently plenty of research is being carried out in academia, industry, and in their joint collaborative projects, such as METIS [4], MiWEBA [5], and MiWaveS [6], in order to study mobile backhaul and radio access networks at higher frequencies.

A main bottleneck for operating at higher frequencies, compared to current cellular frequencies, is a significant increase in the pathloss which is caused by the reduction of the effective antenna area as the frequency increases. This effect will degrade the link budget unless antenna directivity is used to compensate for that [1]. In addition, higher blocking and penetration loss at these frequencies make the coverage challenging especially at NLOS outdoor and outdoor-to-indoor scenarios. Therefore, understanding the propagation properties at higher frequency bands is of key importance to determine their true potentials for the use in 5G cellular communications.

Propagation properties for cellular radio access above 6 GHz are not yet thoroughly investigated in cellular scenarios. It is thus of large interest to get initial insight on the need for updated assumptions and improved models at these frequencies. Researchers are currently investigating the propagation properties at different frequency bands for both outdoor and indoor scenarios (see e.g., [7-9] and references therein).

In this paper, some basic propagation properties at 15 GHz are assessed through radio channel measurements using a 5G radio access prototype. In particular, we present measured coverage for outdoor and outdoor-to-indoor scenarios. We also provide the results for outdoor-to-indoor penetration loss for different blocking objects, including normal and coated windows, human body, a metallic white board, and a concrete pillar. Our results show that both outdoor coverage and outdoor-to-indoor coverage at 15 GHz are limited to areas in LOS with the TP. Moreover, penetration loss by blocking objects can further restrict the indoor coverage. As a means to improve the coverage, we evaluate the potentials of beamforming using simulations.

The rest of the paper is organized as follows: Section II describes the measurement setup and system parameters of the 5G prototype. Section III presents the experimental procedure.
and the measurement environment for outdoor and outdoor-to-indoor measurements. Section IV reports the measurement results and analyses for coverage and outdoor-to-indoor penetration loss of different blocking objects. Performance gain of employing beamforming is also presented in this section. Finally, Section V concludes the paper.

II. 15 GHz Measurement Setup

The measurement equipment is a 5G prototype test system consisting of two TPs and one mobile terminal. The two TPs are installed on the walls of two office buildings at heights 8.5 m (TP1) and 12 m (TP2), respectively, and with an inter-distance of 82 m. For outdoor measurements, the mobile terminal antenna is installed on top of a van at a height 2.9 m (see Fig. 1), while for outdoor-to-indoor measurements it is installed on an electric scooter at a height 1.5 m (see Fig. 3). Two 100 MHz carriers are aggregated into a total of 200 MHz bandwidth. The total transmit power from each TP over the whole 200 MHz bandwidth is 1 W. Each antenna element at the TPs has a maximum gain of 15 dBi, azimuth half power beamwidth (HPBW) of 90°, and elevation HPBW of 8.6°. The mobile terminal antenna element has roughly omni-directional characteristics with -3 dBi gain and 4 dB feeder loss. Corresponding to each carrier, there is an array with two dual-polarized antenna elements at each TP and also at the mobile terminal, enabling 4x4 spatial multiplexing, referred to hereafter as multiple-input multiple-output (MIMO) per carrier.

The radio interface is OFDM with a subcarrier spacing of 75 kHz, a symbol length of 13.3 µs, and a 0.94 µs cyclic prefix. Reference symbols are transmitted from each TP to facilitate the phase and amplitude measurements for all 16 transmit-receive antenna pairs between the mobile terminal and each of the TPs. The measurement resolution is 5 ms in time and 1 MHz in frequency. The channel estimates for the downlink transmissions are logged in the form of both complex channel gains and received signal strength over each 100 MHz band. When received signal strength goes below -75 dBm, the synchronization between the TPs and the mobile terminal is lost. Therefore, -75 dBm is considered as the noise level in our analysis.

III. Measurement Environment and Procedure

In this section, we describe the environment and procedure for the two measurement campaigns that were performed in a square area located in Kista, an urban area in Stockholm, Sweden, with mainly 4-6 floor office buildings (see Fig. 1).

A. Outdoor measurement

For outdoor measurements, the van with the mobile terminal antenna was driven around the square and a majority of nearby streets at a speed of 0-30 km/h (see Fig. 2). The received signal strength was recorded at regular positions along the drive route from each of the TPs independently. The drive route consisted of both LOS and NLOS segments, with additional shadowing provided by e.g. trees and lamp posts.

B. Outdoor-to-indoor measurement

For outdoor-to-indoor measurements, the signal from TP2 is measured inside the building across the street from where TP2 is installed (see Fig. 3) by using the electric scooter with the mobile terminal on floors 3 and 4. The indoor area is an open space with furniture including concrete walls, glass doors, cubicle desks, etc. Two sets of measurements were performed: one to determine the indoor coverage and another set to determine the specific penetration and blocking loss for different materials and objects.

The area coverage was assessed over a mobile walk route according to the solid blue line in Fig. 3. This route is close to the side of the building which is facing TP2. For the penetration loss measurements, the received signal strength at two stationary positions (shown as position A, which is located on floor 3, and position B, which is located on floor 4, in Fig. 3) was recorded in the presence of different objects blocking the LOS between the TP2 and the terminal. In particular, the penetration loss was determined for: 1) a normal window with...
3-layer glass with and without closed metallic blind; 2) a 3-layer window coated with infrared reflective (IRR) glass; 3) human body; 4) a metallic white board; and 5) a wide concrete pillar. The penetration loss was obtained by calculating the difference in the signal strength between unobstructed free space measurement versus the measurement in which blocking materials obstruct the LOS between TP2 and the terminal.

IV. 15 GHz COVERAGE AND PENETRATION LOSS RESULTS

A. Outdoor coverage

Fig. 2 shows the received signal strength for the scanned square and streets for each TP. As can be seen, on the square and along adjacent streets within LOS the coverage is quite good with received signal strength above -65 dBm. However, in NLOS conditions the coverage is limited since the received signal strength quickly decreases towards the noise floor with the present configuration of the test system, i.e. -75 dBm.

Fig. 4 shows the received signal strength as a function of the distance from the mobile terminal to TP1. Blue markers represent all the samples shown in Fig. 2 (left). The peak of antenna main lobe was pointed towards the square at around 50 m distance from TP1. The received signal strength in this location was used to calibrate the measurements and establish a free space reference level, which is indicated by the dashed black line in Fig. 4. Since the elevation beamwidth of the TP antennas was quite narrow, it was not possible to cover the whole measurement route with the peak gain, and hence some locations experienced a lower antenna gain. Additional loss in comparison to the free space reference is caused by shadowing and blocking. The red markers in Fig. 4 represent samples from the street right in front of the antenna and driving south-east in LOS (with the street lined by a few 8-16 m high birch trees without leaves). Compared to the free space reference, there is an offset of about 6 dB which can be attributed to the antenna pattern as discussed above, and further there is a gradually increasing path loss slope which is likely due to shadowing and blocking by trees and other objects along the street. Such dual-slope behavior along LOS streets is well known from measurements at lower frequencies [12]. The model proposed in [12] has also been plotted in the diagram as a red line using the following parameters: 1) $x_0=1$ (first slope propagation constant) 2) $m=4$ (second slope propagation constant) 3) and $x_L=120$ (break point at 120 m). Model parameters matching measurement data from the 15 GHz LOS street (red markers) do not deviate from the 900 MHz parameters in [12], indicating the similarities of the propagation at two frequencies.

Fig. 5 shows the LOS-NLOS transition when turning around the corner marked with a white solid line in Fig. 2. The observed additional loss after the corner is around 20 dB. This does not deviate significantly from what is assumed for LOS-to-NLOS transitions at lower frequency bands. It should, however, be noted that the measured corner loss may be underestimated due to the noise floor limitation. The rather steep loss slope is also observed in corresponding coverage maps in Fig. 2.

B. Outdoor-to-indoor penetration loss

The measured penetration loss for different window configurations and blocking objects are listed in Table I. The window loss is also compared with the model suggested in [10]. According to this model, the window loss is calculated as...
loss within this open office area is in the order of 1 dB/m. The variance in signal strength is larger for the area closer to the outer wall. This can be attributed to the impact of obstacles and wall structure along the propagation path to each part of the walk route. In fact, the larger number of obstacles and scattering in the lower part of the walk route could explain the smaller variance in the signal strength. It seems that outdoor-to-indoor coverage at 15 GHz is mainly limited to the part of the building near the external wall that is illuminated by the outdoor TP. Coverage deeper into the building appears to be challenging using these antenna directivities.

### Table I. WINDOW AND OBSTACLE BLOCKING LOSS

<table>
<thead>
<tr>
<th>Blocking Object</th>
<th>Measured loss</th>
<th>Model [5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-glass ordinary window</td>
<td>6 dB</td>
<td>7.5 dB</td>
</tr>
<tr>
<td>…with closed blind</td>
<td>14 dB</td>
<td></td>
</tr>
<tr>
<td>3-glass IRR coated window</td>
<td>24 dB</td>
<td>27.5 dB</td>
</tr>
<tr>
<td>Body 30 cm from UE antenna</td>
<td>10 dB</td>
<td></td>
</tr>
<tr>
<td>2x1 m metallic whiteboard</td>
<td>10 dB</td>
<td></td>
</tr>
<tr>
<td>…3 m from UE antenna</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 m wide concrete pillar</td>
<td>8 dB</td>
<td></td>
</tr>
<tr>
<td>5 m from UE antenna</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Coverage extension by beamforming

As mentioned in Section II, multiple antennas at both the TPs and the mobile terminals have been used to spatially multiplex several data streams over the channel. This approach is mainly helpful when the aim is to increase the throughput. Multiple antennas can also be used to perform beamforming in order to provide increased signal strength at the receiver. Beamforming is particularly relevant at higher frequencies where the transmitted signal suffers from a higher path loss compared to current cellular frequencies. In this section, we present the potential gain in the signal strength that can be achieved by using beamforming.

For this purpose, we consider a segment of the outdoor measurement route for TP1 containing mainly LOS positions (see Fig. 2 (left)). For each position on the route, we use the 4x4 MIMO channel estimates that were recorded over 100 frequency bins during the measurement. We compute the signal strength using SVD-based beamforming over each of the measured 100 frequency bins. We next average the beamformed signal strength over all the frequency bins to obtain average beamformed signal strength per frequency bin. We then obtain the average signal strength per frequency bin without beamforming and subtract it from the average beamformed signal strength per frequency bin to obtain the average beamforming gain. Fig. 8 shows the CDF of the average beamforming gain over the considered route. It is observed that beamforming can bring between 10 to 12 dB gain.
in the signal strength per frequency bin on average. This is quite close to the theoretical 12 dB gain of a 4x4 MIMO channel with unit amplitude of all 16 channel coefficients despite the fact that non-ideal and dual-polarized antenna elements were utilized. Such an increase can further extend the coverage to locations that suffer from severe path loss, e.g., NLOS in outdoor and indoor. More detailed investigation of this issue is a topic for future research.

V. CONCLUDING REMARKS

The measurements have shown that outdoor microcellular coverage in LOS and in lightly shadowed areas is possible at 15 GHz with similar antenna directivity as presently used in cellular networks. The path loss characteristics at 15 GHz are quite similar to those experienced at cellular frequencies, with the addition of the 20*log10(f) frequency dependence of the effective antenna area of an isotropic antenna. This effect in combination with the 200 MHz bandwidth and a limited 1 W output power makes it very challenging to achieve NLOS coverage due to the increased propagation loss observed when passing a corner into NLOS, going into a building, or blocking the propagation path by obstacles such as human body and normal and coated windows.

However, considering the smaller wavelength at higher frequencies, the directivity of the antenna can be significantly improved using adaptive beamforming without increasing the antenna form factor compared to cellular frequencies. This potential was only briefly explored in this paper through simulation where 4 transmit and 4 receive antennas made it possible to increase the received signal strength by 10-12 dB. Further work is required to quantify the potential coverage extension when employing more antenna elements.

REFERENCES