Suburban Fixed Wireless Access Channel Measurements and Models at 28 GHz for 90% Outdoor Coverage

Jinfeng Du, Member, IEEE, Dmitry Chizhik, Fellow, IEEE, Rodolfo Feick, Senior Member, IEEE, Mauricio Rodriguez, Member, IEEE, Guillermo Castro, and Reinaldo A. Valenzuela, Fellow, IEEE

Abstract—Achieving adequate coverage with high gain antennas is key to realizing the full promise of the wide bandwidth available at mm/cm bands. We report extensive outdoor measurements at 28 GHz in suburban residential areas in New Jersey and Chile, with over 2000 links measured for same-street links (vegetation blocked LOS) from 13 streets and other-street links (true NLOS) from 7 streets, using a specialized narrowband channel sounder at ranges reaching 200 m. The measurements, applicable to fixed wireless access, involved a 55° transmit antenna placed on the exterior of a street-facing window and a 10° receive horn antenna spinning on top of a van mast at 3 m height, emulating a lamppost-mounted base station. Measured path gain-distance dependence is well represented by power-law models, and azimuth gains at the base are degraded through scattering by more than 4.3 dB for 10% of links. It was found that, with 51 dBm EIRP at the FW A base station and 11 dBi antenna at CPE, 1 Gbps downlink rate can be delivered to an outdoor mounted CPE for up to 100 m from a base station deployed in the same street with 90% coverage guarantee.

Index Terms—Fixed wireless access, propagation, measurement

I. INTRODUCTION

The wide spectrum available at cm/mm bands promises very high rates. However, higher free-space, scattering, transmission and diffraction losses in these bands must be overcome [1]. To overcome such losses one cannot count on the nominal (free-space) gain of an antenna, as this may be significantly reduced by scattering [2], [3]. Moreover, temporal fluctuation can pose beam adaptation requirements. Here we focus on the fixed wireless access (FWA) deployment in suburban environments at 28 GHz to assess its capability in providing high-speed broadband access to residential customers. The case of interest involves a beam-steering antenna at lamppost height (3m - 6m) with user terminals on the exterior of single-family homes along a street, in the presence of vegetation. We collected a statistically significant set of path gains, effective antenna gains as well as fluctuation characteristics to reliably describe performance at 90% of locations in a typical outdoor suburban environment.

Numerous measurement campaigns have largely concentrated on urban areas, particularly at higher frequencies [1], [4]–[13]. A more comprehensive survey of measurements at mmWave bands can be found in [12]–[14]. The data is generally separated into line of sight (LOS) and non-line of sight (NLOS) categories. Path loss for each was characterized with slope-intercept models. Haneda et al. [7] presented path loss models based on measurements in urban canyons in multiple cities. Same street LOS measurements were unobstructed by vegetation, with NLOS defined as being around-the-corner, and the 3GPP 36.814 UMi NLOS model with Manhattan grid layout was modified to include a frequency dependent turn loss at the corner. This approach was also adopted in [10]–[12], where the around corner model was extended to many corners based on ray-tracing data from a 3D building database (cars, street signs, and billboards are not considered). The majority of the previous mmWave outdoor measurements were carried out in urban city street canyons (tall and continuous buildings on both side, almost no vegetation blockage) or university/industry campus (open space), which is quite different from suburban residential areas where blockage of trees/bushes is an important factor for signal attenuation. In [9] suburban measurements were carried out by placing a transmitter at a height of 7.5m in a street (mimicking a base), and moving the receiver either along the same street, or into two nearby streets that are perpendicular to the street with the transmitter. The slope for same-street path loss was found to be close to 3 when using an omni-antenna, and higher path loss was reported when using a directional antenna (peak power in angular domain was used).

In this paper, we focus on path gains, effective antenna gains as well as temporal fluctuation to reliably describe performance at 90% of locations in a typical outdoor suburban environment for FWA. To obtain results on these issues we used a specially constructed narrowband channel sounder, allowing rapid measurements of directional channel response, with large dynamic range (even in the absence of antenna gain). Fast data collection allows both an assessment of channel fluctuation scale as well as permitting rapid gathering of statistically significant data. We separate, as is traditional, the path gain measurements from the directional aspects of the channel. This is done by averaging over all directions the measured power to provide an effective average power that an
omni antenna would have measured. Directional (azimuthal) gain is estimated separately from normalized angular spectra. We collected a statistically significant set of links (more than 2000) in two towns (one in NJ and the other in Chile). They consist of same-street links (vegetation blocked LOS) from 13 streets, and other-street links (true NLOS) from 7 streets. Despite the rich diversity of house/tree types and density, the power law slope-intercept fits to measured path loss from NJ and from Chile are similar. Main contributions include statistically significant characterization of the suburban fixed wireless channel, including slope-intercept representation of path loss, variability of path loss between nominally similar streets, statistical distributions of azimuth gain degradation, potential gain due to beam re-aim in fluctuating channels and evaluation of available rates of suburban fixed wireless links.

The rest of the paper is organized as follows: A brief description of the measurement equipment and environment is presented in Sec. II, and path gain measurement and models for suburban street canyon are presented in Sec. III. Effective azimuth antenna gain results are reported in Sec. IV and the benefit of re-aiming after each azimuth scan is quantified in Sec. V. Outdoor-to-outdoor downlink rate with 90% service guarantee is evaluated in Sec. VI and conclusions are presented in Sec. VII.

II. MEASUREMENT EQUIPMENT AND ENVIRONMENT

A. Measurement equipment

To maximize data collection speed and link budget, we constructed a narrowband sounder, transmitting a 28 GHz continuous-wave (CW) tone at 22 dBm power. The transmitter has a 10 dBi horn with 55° half-power beamwidth in both elevation and azimuth. The receiver has a 10° (24 dBi) horn, connected to low-noise amplifier, a mixer, and a power meter, with a 20 kHz receive bandwidth and effective noise figure of 5 dB. The transmitter and receiver have free running local oscillators, with a frequency accuracy better than 10⁻⁷. The receiver horn was mounted on a rotating platform allowing a full angular scan every 200 ms. The receiver records power samples at a rate of 740 samples/sec, using an onboard computer. The system was calibrated in the lab and anechoic chamber to assure absolute power accuracy of 0.15 dBm. The full dynamic range of the receiver (from noise floor to 1 dB compression point) was found to be 50 dB, extensible to 75 dB using switchable receiver amplifiers. In combination with removable transmit attenuators, measurable path loss allowing at least 10 dB SNR ranged from -62 dB (1 meter in free space) to -137 dB (200 m range with 30 dB excess loss). Measurable path loss extends to 171 dB with directional antenna gains.

The rotating 10° horn receiver was tested in an open field at a range of 40 meters from the transmitter. The measured receive pattern is seen in Fig. 1 to be within 1 dB of that measured in the anechoic chamber, down to -40 dB.

B. Measurement environment

Measurements were performed at 28 GHz in suburban residential areas in New Jersey and Viña del Mar, Chile. The New Jersey suburb has mostly 2-story wood-frame homes along 25 m-wide streets. The vegetation along the streets and on properties consisted of tall trees and bushes, representative of North-Eastern US. The Chilean suburbs have narrower streets and denser houses as compared to NJ, and the front yards are often surrounded by a metal fence and low-height bushes.

A 55° horn antenna, emulating a user terminal, was placed near the exterior of a street-facing window aiming at 45° (bisecting the 90° angle between the normal to the house wall and the direction along the street) to illuminate the street towards the base station (sometimes just inside but pointing out through an open window), while a 10° horn receiver, spinning at up to 300 rpm, was placed on a van mast 3 m above ground. Narrowband receive power was recorded as a function of azimuth angle and time. The van was driven along the street, stopping every 1m - 3m to collect measurements at ranges from 20 m - 200 m from the user terminal. A typical measurement geometry is illustrated in Fig. 2. Each link measurement lasted 10 seconds and consisted of at least 37 full azimuthal scans, each with 360 power measurements. A total of over 1700 link measurements were made, using 6 houses in NJ and 5 houses in Chile, for the “same-street” deployment scenario where the serving base station and the CPE are on the same street, but the direct path was normally blocked by trees or bushes. The “other-street” scenario, where the base station and the CPE are on a contiguous parallel street, was measured using 4 streets in NJ and 3 streets in Chile.

C. Computation of path gain and effective azimuthal gain from measurements

The rotating receive horn provides a measurement set of power as a function of azimuth and time. Our goal is to determine overall path loss suffered by the signal, and, separately the distribution of the signal over angle, to determine beamforming effectiveness. It can be shown [4] that averaging power measurements $P(\phi)$ over azimuth $\phi$ using a directive...
antenna has the same expected value as local spatial average $<P_{\text{omni}}>$ of an azimuthally omnidirectional antenna:

$$< P >_\phi = \frac{1}{2\pi} \int_0^{2\pi} P(\phi') d\phi' = < P_{\text{omni}} >. \quad (1)$$

This remains so despite the beam overlap between successive azimuthal aiming of the rotating horn antenna.

Path gain $P_G$ is computed from azimuthally averaged received power $< P >_\phi$ by removing transmit power $P_T$ and elevation gain $G_{\text{elev}}$:

$$P_G = < P >_\phi / (P_T G_{\text{elev}}). \quad (2)$$

The elevation gain is obtained from the total ideal antenna gain $G_{\text{tot}}$ (as measured in the anechoic chamber):

$$G_{\text{elev}} = G_{\text{tot}} / G_{\text{azim}}, \quad (3)$$

where the ideal azimuthal antenna gain is given by the peak-to-average ratio of the antenna pattern $G(\phi)$, i.e.,

$$G_{\text{azim}} = G_{\text{max}} / < G >_\phi. \quad (4)$$

Accordingly, the effective azimuthal gain is obtained from (4) by using the measured power $P_{\text{max}} = \max P(\phi')$ and $< P >_\phi$.

III. PATH GAIN MEASUREMENTS AND MODELS FOR SUBURBAN STREET CANYON

A. Outdoor-outdoor LOS with ground reflection

An outdoor LOS calibration was carried out in an open field where the 10° horn was on the van mast 3 m above ground and the 55° horn was 1 m above ground. The measured path gain is shown in Fig. 3 together with a model from 2 ray theory which includes antenna pattern (to account for vertical misalignment at short distance) and nominal ground reflectivity. The data exhibits constructive and destructive superposition in agreement with theory, with peaks about 6 dB above free space, and nulls that are more than 15 dB deep. Both observed and modeled path gains for distances shorter than 30 m are lower than free space caused by vertical misalignment, where links that are 20 m or shorter will be out of the 10° receive beam.

B. Same-street outdoor-outdoor with vegetation

Over 1700 link measurements were made for the same-street deployment scenario. Path gain for each measured link is computed by averaging power over all angular directions to estimate the local average power as would be obtained from a spatial average of omni-antenna measurements. The results hold despite beam overlap in successive pointing directions. Measured same-street path gain as a function of distance $d$ (in meters), shown in Fig. 4 (upper), was found to be well represented by

$$P_{\text{same-street}} = -45.1 - 40.6 \log_{10} d \ (dB), \quad (5)$$

with RMS deviation of 6.4 dB. As compared to free space, it has a 25 dB excess loss at 100 m.

A model derived from diffuse theory [15] had a slope of 4.0 and RMS error of 6.8 dB, comparable to the linear fit predictions, which is notable for a theory unadjusted to data and given the fact that the impact of vegetation blockage loss was here accounted for by modeling the layer of non-contiguous vegetation as a contiguous diffuse media. We note that the slope of 4.06 obtained from slope-intercept fit is very close the slope predicted by the model derived from diffuse theory. The 3GPP 38.901 [16] urban micro street-canyon NLOS model (indicated by the solid blue line), which is intended to use for NLOS propagation in urban streets, had an error of 6.6 dB, comparable to the 6.4 dB RMS deviation from the linear fit to data. It should be noted, however, the 38.901 model prescribes the use of LOS and NLOS formulas, based on specified Probability of Line of Sight, that is set to 1
for ranges under 18 m and decreases to 0.5 at 50 m and 0.25 at 100 m. In LOS, the path gain is specified as being close to free space. Over 90% of measurements in Fig. 4 (upper) had excess losses relative to free space of over 10 dB, even at ranges of 50 m, despite being on the same street.

Measured data from NJ and Chile match each other well with similar slopes and spread, and comparing the Chile dataset against the NJ slope-intercept fit resulted in less than 0.3 dB increase of RMS error (7.2 dB RMS of Chile dataset against its own fit). Line fits to the measured path gain for the two datasets and their combination are summarized in Table I. Applying the Common-Slope Cross-Comparison method [17] to the two datasets resulted in a common slope of 4.05 and a 1 dB gap between the two intercepts with combined RMS fitting error of 6.4 dB. Therefore, we can conclude that the empirical model presented in (5) is robust.

Distributions of measured path gain for ranges of 20 m to 200 m (uniformly sampled) are plotted separately for each street in Fig. 5. It may be observed that distributions vary substantially, with medians spanning a range of 13 dB. This illustrates the importance of collecting sufficient data over multiple streets and houses to get representative path loss. Modeling one street based on a data fit to data collected on another street may lead to some 13 dB (median) error in coverage.

### C. Other-street outdoor-outdoor measurement

To assess the possibility of high throughput coverage from lamp post-mounted base stations to terminals located in a different street, we collected over 180 “other-street” links where the user terminal was placed at a house of one street, and the base moved along a parallel street(s) separated by one block of 30 to 50 m wide. Measured other-street path gain, shown in Fig. 6 was found to be well represented by

$$P_{other-street} = -80.3 - 31.3 \log_{10} d \text{ (dB)},$$

where $d$ is the Euclidean distance between base and user terminal. RMS deviation was found to be of 4.8 dB. As compared to free space, it has a 42 dB excess loss at 100 m, in contrast to the 25 dB excess loss in the same-street model. Coverage from under-clutter base stations located in other streets is thus very limited, and the potential interference from other-street base stations is likewise mild, since the latter is typically 10 to 17 dB lower than the same-street signal even if the two links have the same distance. We note that using the same-street model (5), to represent other-street data, resulted in RMS error of 18.3 dB, justifying the use of a separate model (6) for other-street links (for example, to assess interference or the viability of coverage from base stations on parallel streets).
Figure 6. Measured path gain for over 180 other-street links along each street (differs in color) resulted in a slope of -3.13, intercept of -80.3 dB, and RMS error of 4.8 dB. As compared to free space, it has a 42 dB excess loss at 100 m. Using the same-street model to represent other-street data resulted in RMS error of 18.3 dB.

Figure 7. Empirical observation of tree blockage from two different TX antenna heights (TX1 at 3m and TX2 at 1.5m) recorded more than 20 dB loss. The shortest distance from the rotating RX to the branches/leaves is about 2 meters during the measurement.

D. Outdoor-outdoor visual LOS links

Scatterers/obstructions within the first radio Fresnel zone can potentially cause significant power drop even in the presence of an optical line-of-sight path (as verified with a flashing light). To evaluate this, we plotted in Fig. 7 some empirical observations of the effect of (partial) blockage by tree branches of the visual LOS links. The user terminal (TX) is placed either at 1 m or 3 m height on the street-facing exterior wall, and the base (RX) is moving along the street, stopping every meter, to collect measurements. As the base station moves along the street, the links change from LOS to NLOS and then back to LOS. Partial blockage was observed to result in 5 to 10 dB losses over free space propagation. In contrast under total blockage, more than 20 dB excess loss was observed.

For links ranging from 30 -100 m, the maximum radius of the first Fresnel zone is several tens of centimeters at 28GHz. This leaves ample opportunity for the actual visual LOS path to survive despite partial blockage from branches/leaves. We labeled the same-street links that have a visual LOS path, as determined by using a flashing light at the one end of the links and observed at the other end, and plotted their path gain versus distance in Fig. 8. Using line fit with fixed intercept of Friis path gain at 1m, the visual LOS path gain dependence on distance d was found to be well represented by

$$P_{\text{visual-LOS}} = -6.14 - 24.4 \log_{10} d \text{ (dB)},$$ (7)

with RMS deviation of 4.2 dB. In contrast to the previous cases we here used the free space path loss as intercept since our data set is now limited to the points closest to that condition. Optimizing intercept and slope resulted in no more 0.2 dB reduction of RMS error.

As compared to free space, the measured excess loss can be up to 15 dB for links at various distances as shown in Fig. 8. The optical LOS condition thus does not imply free space propagation loss.

IV. AZIMUTH GAIN MEASUREMENTS

Nominal antenna gain can be degraded as a result of significant angular spread compared to beam width in scattering environments. To reliably quantify this effect, we measured power as a function of azimuth as the 10o horn was spinning. For every Tx-Rx pair the effective azimuth gain was computed as the ratio of the maximum power to the average over all directions, as justified in [3] under the assumption of uncorrelated scattering. This allows us to quantify the effective beamforming (BF) gain directly, without explicitly determining the channel angular spectrum, which is different from the approach adopted by [2] where an estimated channel angular spectrum was used. The resulting distribution of azimuth gains is shown in Fig. 9. The azimuth gain exceeded in 90% of cases at the 3 m base station in the street is found to be 10.2 dBi, as opposed to the nominal gain of 14.5 dBi in azimuth, i.e., a 4.3 dB gain reduction. From this degradation we can estimate.
the RMS angle spread to be 14°, assuming Gaussian-shaped channel angular spectrum.

To investigate the possible benefits of using a more directive antenna at the customers premise, we placed the spinning horn antenna near the house wall (in proximity of vegetation), and obtained an azimuth gain of 8 dBi at the 90th percentile, a 6.5 dB gain reduction corresponding to 22° RMS angle spread (leftmost curve in Fig. 9). The observed effective azimuth gains replace the nominal antenna gain in link budget calculations.

We found that the effective gain distribution for the base station varies mildly from street to street, with medians ranging from 11.2 to 14 dBi, and no clear distinction has been observed between same-street and other-street measurements. Log-normal fits (thin lines) to the empirical CDFs of effective azimuth gain in street and at house have means of 12.4 dB and 9.5 dB, respectively, with a standard deviation of 1.5 dB. Using a more advanced base antenna of the same aperture (e.g. combining multiple beams), which requires channel station information and additional RF chains, may bring additional gain, upper-bounded by 4.3 dB in 90% of locations in this environment.

V. POTENTIAL GAIN OF BEAM RE-AIM AT EACH AZIMUTH SCAN

Changing beam direction may compensate for temporal fades. We quantify temporal fluctuation of received power along azimuth directions, mainly caused by wind-blown branches/leafs, could be quantified by computing the temporal K-factors of the observed channels. We measured the angular spectrum over time and select the direction that provides the best-on-average power over time, referred as the best (a posteriori) angle. For each link, there are more than 37 power measurement along the best angle, and we computed the temporal K-factor using the method of moments (MoM) [20]. The CDFs of the temporal K-factor for each street, and for the ensemble of all streets are plotted in Fig. 10, where the median value of each street ranges from -2 to 24 dB. The ensemble of temporal K-factors for all the same-street links is well represented by a log-normal distribution with mean 16.7 dB and standard deviation 8.9 dB. The same-street links in general have higher K-factors (median 16 dB) than other-street links (median 2.5 dB). This can be explained by the fact that there are more trees/vegetation between the Tx and Rx for other-street links. Moving vehicles may also contribute to the lower K-factors for other-street links as we had no control of the traffic in the streets where the CPE was located when moving the base station along other streets. Same-street measurements were collected during intervals where no moving vehicles were observed.

For the angular spectrum measured at each link, we choose the highest power direction for each turn, referred as instantaneous best direction. This creates a sequence of instantaneous best directions over time, relevant when the azimuthal scan measurement is fast enough to assure best-aim is maintained over time. In Fig. 11 we plot the CDFs of power change between consecutive turns for the instantaneous best direction of each turn (blue lines) and for power along the best-on-average (a posterior direction (red lines) for each link. As seen, for same-street links the fluctuation of the best per-rotation power sample and the sample for the best-on-average angle is very small. This suggest that beamswitching will offer very modest gains. More than 90% of all same-street links experienced less than 3 dB power fluctuation between consecutive turns (about 200 ms) and the corresponding beamswitching gain is less than 1 dB. However, power fluctuation is more severe for other-street links, with 8 dB power fluctuation along the best angle at the 90th percentile and a potential beamswitching gain of 3 dB.

![Figure 9. CDFs of effective azimuth gain of the spinning horn antenna, where the degradation is 4.3 dB at 10-th percentile when placed in streets (as base station) and 6.5 dB at houses (as CPE). Best log-normal fits (thin lines) have mean of 12.4 dB and 9.5 dB, respectively, with a standard deviation of 1.5 dB.](image1)

![Figure 10. CDFs of temporal K-factor along the best (a posteriori) angle for each link measured in NJ, with median values range from -2 to 24 dB. Solid lines are same-street links (median 16 dB) and dashed lines are for other-street (median 2.5 dB). The ensemble of temporal K-factor for all the same-street links is well represented by a log-normal distribution with mean 16.7 dB and standard deviation 8.9 dB.](image2)
VI. ESTIMATES OF ACHIEVABLE OUTDOOR-TO-OUTDOOR
DOWLINK RATES FOR 90% COVERAGE

To evaluate the edge rate for 90% coverage based on the findings reported above, we computed the Shannon rate for outdoor CPEs with 10th percentile SNR (i.e., 90% CPEs have higher SNR). The base station is assumed to have 28 dBm transmit power using a 23 dBi nominal gain antenna and bandwidth of 800 MHz and the outdoor CPE has 11 dBi antenna gain with 9 dB noise figure. Both transmitter and receiver are assumed to be equipped with a single RF chain and use simple directional antennas, pointed adaptively so as to get maximum power. Given the modest degradation of azimuth gain and modest temporal variations found in this campaign, such a simple system is seen here as a reasonable reference. For each link, the path gain was generated from a random process as described by either (5) or (6) for same-street and other-street scenarios, respectively, and the effective azimuth gain was generated using the log-normal fits from Sec. IV. Channel dynamics caused by wind-blown leaves/branches was not included in the calculation as they were found to be a minor effect in our measurement. For each base-CPE separation distance, 10000 links are generated randomly and independently, from which we obtain the Shannon rate with 90% coverage guarantee for that distance. The resulting rate-distance plots are shown in Fig. 12. It was found that 1 Gbps downlink rate can be delivered to outdoor CPE in the same street for distance up to 100 m with 90% coverage guarantee, and the rate decreases to 80 Mbps when the distance increases to 200 m. If the base station and the CPE are in different streets, 100 Mbps downlink rate can be delivered up to 80 m with 90% coverage guarantee. Since outdoor-to-indoor penetration loss is large, 9 to 17 dB median loss as reported in [17] for NJ suburban residential homes, the corresponding ranges will decrease by a factor of 2 or more. Compared to a cellular small cell operating at 2 GHz band (using 30 dBm transmit power and 5 dBi antenna gain for both the base station and the UE), 28 GHz cell can deliver higher rate (with 90% coverage guarantee) than the 2 GHz system over the 200 m range for same-street CPEs. Should 100 MHz bandwidth be available for the 2 GHz system (for example, via carrier aggregation), the rate at 100 m with 90% coverage guarantee would be increased to 400 Mbps, about half of what can be supported by the 28 GHz system using 800 MHz. The path loss and angular spread for the 2 GHz system are generated using 3GPP 36.814 UMi NLOS models specified in [21]. On the other hand, a conventional 2 GHz system using 20 MHz would deliver higher rates than an 800 MHz-wide 28 GHz system beyond 60 m in general NLOS conditions, where the base station is not on the same street as the terminal being served.

VII. CONCLUSIONS

Extensive measurements (over 2000 links, each containing at least 37 full azimuthal scans with 360 power measurements) of path loss, achievable azimuth gain and temporal fading were collected and characterized statistically at 28 GHz in suburban environments in NJ and Via del Mar, Chile. The same-street path loss fit has a slope of 4.1 with 25 dB excess loss over free space at 100 m, and the other-street path loss fit has a slope of 3.1 with 42 dB excess loss at 100 m. Links that have visual LOS path (assured using a flashlight) suffer up to 15 dB excess loss over free space over a wide range of distances. An ordinary 25 dBi directional antenna with adaptive aim was used to maintain coherent transmission.
found to lose up to 4.3 dB of gain in 90% of suburban links. Using multiple chains within the same antenna aperture can help recover some of this loss, upper bounded by 4.3 dB. In the absence of moving vehicles, the benefit of rapidly re-aiming the beam at each azimuth scan is less than 2 dB. It was found that, with typical power and antenna gain configuration for FWA base station and CPE, 1Gbps downlink rate can be delivered to an outdoor mounted CPE for up to 100 m from a base station deployed in the same street with 90% coverage guarantee. If the base station and the CPE are in different streets, 100 Mbps downlink rate can be delivered up to 80 m with 90% coverage guarantee. The corresponding downlink edge rate will be significantly reduced when moving outdoor CPE to indoor, highlighting the challenge for FWA deployments.

ACKNOWLEDGMENT

The authors wish to acknowledge support by CONICYT under Grant Proyecto Basal FB0821 and to Proyecto VRIEA-PUCV 039.462/2017 for supporting Mauricio Rodriguez and Guillermo Castro. Many thanks to Hector Carrasco, Leonardo Guerrero and Rene Pozo for designing and building the platform, Cuong Tran for essential diagnostics and repair, and Alicia Musa for data collection software improvement.

REFERENCES

[1] T. S. Rappaport et al., “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!,” IEEE Access, vol. 1, pp. 335–349, 2013.
[2] L. J. Greenstein and V. Erceg, “Gain reductions due to scatter on wireless paths with directional antennas,” IEEE Communications Letters, vol. 3, pp. 169–171, June 1999.
[3] D. Chizhik, J. Du, R. Feick, G. Castro, M. Rodriguez and R. A. Valenzuela, “Path loss, beamforming gain and time dynamics measurements at 28 GHz for 90% indoor coverage,” arXiv: 1712.06580, Dec. 2017.
[4] J. Ko, Y.-J. Cho, S. Hur, T. Kim, J. Park, A. F. Molisch, K. Haneda, M. Peter, D. Park, D.-H. Cho, “Millimeter-wave channel measurements and analysis for statistical spatial channel model in in-building and urban environments at 28 GHz,” IEEE Trans. Wireless Communications, vol. 16, pp. 5853–5868, Sep. 2017.
[5] V. Raghavan, A. Partyka, L. Akhoondzadeh-Asl, M. A. Tassoudji, O. H. Koymen and J. Sanelli, “Millimeter wave channel measurement and implications for PHY layer design,” IEEE Transactions on Antennas and Propagation, vol. 65, pp. 6521–6533, Dec. 2017.
[6] K. Haneda et al., “5G 3GPP-like channel models for outdoor urban microcellular and macrocellular environments,” IEEE Vehicular Technology Conference (VTC Spring), May 2016.
[7] K. Haneda, N. Omaki, T. Imai, L. Raschkowski, M. Peter and A. Roivainen, “Frequency-agile pathloss models for urban street canyons,” IEEE Transactions on Antennas and Propagation, vol. 64, pp. 1941–1951, May 2016.
[8] “5G Channel Model for bands up to 100 GHz, Annex A: Summary of channel sounding, simulations and measurement data,” 3GCM White Paper, Mar. 2016, [http://www.5gworkshops.com/3GCM.html]
[9] C. U Bas, R. Wang, S. Sangodoyin, S. Hur, K. Whang, J. Park, J. Zhang and Andreas F. Molisch, “28 GHz Micrcell Measurement Campaign for Residential Environment,” arXiv:1711.00170, Nov. 2017.
[10] A. Karttunen, A. F. Molisch, S. Hur, J. Park and C. J. Zhang, “Spatially Consistent Street-by-Street Path Loss Model for 28-GHz Channels in Micro Cell Urban Environments,” IEEE Transactions on Wireless Communications, vol. 16, pp. 7538–7550, Nov. 2017.
[11] T. S. Rappaport, G. R. MacCartney, S. Sun, H. Yan and S. Deng, “Small-Scale, Local Area, and Transitional Millimeter Wave Propagation for 5G Communications,” IEEE Transactions on Antennas and Propagation, vol. 65, pp. 6474–6490, Dec. 2017.
[12] R. Wang, C. U. Bas, S. Sangodoyin, S. Hur, J. Park, J. Zhang and A. F. Molisch, “Stationarity region of Mm-Wave channel based on outdoor microcellular measurements at 28 GHz,” IEEE Military Communications Conference (MILCOM), Baltimore, MD, 2017, pp. 782-787.