Millimeter-Wave Distance-Dependent Large-Scale Propagation Measurements and Path Loss Models for Outdoor and Indoor 5G Systems

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Abstract—This paper presents millimeter-wave propagation measurements for urban micro-cellular and indoor office scenarios at 28 GHz and 73 GHz, and investigates the corresponding path loss using five types of path loss models, the single-frequency floating-intercept (FI) model, single-frequency close-in (CI) free space reference distance model, multi-frequency alpha-beta-gamma (ABG) model, multi-frequency CI model, and multi-frequency CI model with a frequency-weighted path loss exponent (CIF), in both line-of-sight and non-line-of-sight environments. Results show that the CI and CIF models provide good estimation and exhibit stable behavior over frequencies and distances, with a solid physical basis and less computational complexity when compared with the FI and ABG models. Furthermore, path loss in outdoor scenarios shows little dependence on frequency beyond the first meter of free space propagation, whereas path loss tends to increase with frequency in addition to the increased free space path loss in indoor environments. Therefore, the CI model is suitable for outdoor environments over multiple frequencies, while the CIF model is more appropriate for indoor modeling. This work shows that both the CI and CIF models use fewer parameters and offer more convenient closed-form expressions suitable for analysis, without compromising model accuracy when compared to current 3GPP and WINNER path loss models.

I. INTRODUCTION

The tremendous amount of raw available bandwidth at millimeter-wave (mmWave) frequency bands is an attractive resource to deliver multi-Gigabit-per-second (Gbps) data rates [1], [2], and to relieve the mobile data traffic congestion in lower frequency bands, e.g., below 6 GHz. Fifth generation (5G) wireless communication systems that use mmWaves have been a research focus over the recent few years, and many research groups and industry entities have been conducting measurements and/or developing channel models at mmWave frequencies. For instance, outdoor propagation measurements and modeling at 60 GHz were carried out in various city streets [3], [4]. Aalto University performed outdoor channel measurements over 5 GHz of bandwidth from 81 GHz to 86 GHz in the E-band for point-to-point communications in a street canyon scenario in Helsinki, Finland [5]. 28 GHz channel propagation measurements and models have been conducted by Samsung and NYU WIRELESS for 5G mobile communications [2], [6], [7].

For both outdoor and indoor wireless communications networks, estimating large-scale path loss is important for modeling communications systems over distance and/or frequency, thus it is critical to accurately model path loss with users of the models in mind. When selecting models, those with fewer parameters that offer an intuitive or physics-based rationale, and that also have convenient closed-form expressions and provide repeatability and stability of parameters across many different data sets should be preferred over more complicated models that stray from the physics of propagation and offer widely varying model parameters when applied to different sets of data in similar physical environments.

Path loss models from empirical and simulated measurements are typically generated via two approaches: [2]: ones that have some anchor based on the physics of transmitted power close to the antenna (such as the close-in (CI) free space reference distance model [2]), and ones that do a mathematical curve fitting over the data set without any physical anchor to the transmitted power (such as the floating-intercept (FI) model [3],[9]). The propagation models for mmWave frequencies in the ITU-R P-series [10] consider free space loss and various additional effects such as tropospheric scatter and gaseous absorption, which are already inherently included in the CI and FI models.

In this paper, extensive propagation measurements for the urban micro-cellular (UMi) street canyon (SC) scenario and indoor office scenario in New York City at mmWave frequencies of 28 GHz and 73 GHz are presented. Using the measured data, path loss results are studied and compared with five types of path loss models, the single-frequency FI model, the single-frequency CI model, the multi-frequency alpha-beta-gamma (ABG) model, the multi-frequency CI model, and the multi-frequency CI model with a frequency-weighted path loss exponent (CIF). Note that each of the five path loss models has a single slope, and dual-slope models can be constructed as long as continuity is maintained at the breakpoint [11], but only marginal improvement in standard deviations (less than a dB) is typically obtained at the expense of additional model parameters and complexity.
II. MILLIMETER-WAVE PROPAGATION MEASUREMENTS

A. Outdoor Measurements

In the summers of 2012 and 2013, two outdoor propagation measurement campaigns were conducted at 28 GHz and 73 GHz, respectively, in downtown Manhattan, New York, where more than 10,000 directional power delay profiles (PDPs) were recorded using similar 400 Megachips-per-second (Mcps) spread spectrum sliding correlator channel sounders and directional steerable horn antennas at both the transmitter (TX) and receiver (RX) to investigate mmWave channel characteristics in a dense UMi environment [1], [2]. The measurement system provided an RF first null-to-null bandwidth of 800 MHz and multipath time resolution of 2.5 ns. With the measurement system, the total time to acquire a PDP (including recording and averaging 20 instantaneous PDPs) was 40.94 ms × 20 = 818.8 ms, where 40.94 ms was the time it took to record a single PDP capture for a particular antenna pointing direction [2].

For the 28 GHz measurements conducted in Manhattan, three TX locations (heights of 7 m) and 27 RX locations (heights of 1.5 m) were selected [2]: a pair of 24.5 dBi-gain steerable directional horn antennas was used at the TX and RX with 10.9° and 8.6° half-power beamwidths (HPBWs) in the azimuth and elevation planes, respectively. For nine of the ten measurement sweeps for each TX-RX location combination (except two line-of-sight (LOS) RX locations), the RX antenna was sequentially swept over the entire azimuth plane in increments of one HPBW at elevation angles of 0° and ±20° about the horizon, so as to measure contiguous angular snapshots of the channel impulse response over the entire 360° azimuth plane at the RX, while the TX antenna remained at a fixed azimuth and elevation angle. For the final (tenth) measurement sweep, the TX antenna was swept over the entire azimuth plane at a fixed elevation (-10°), with the RX antenna at a fixed azimuth and elevation plane [1].

For the 73 GHz measurements, five TX locations (heights of 7 m and 17 m) and 27 RX locations were used, with RX antenna heights of 2 m (mobile scenario) and 4.06 m (backhaul scenario), yielding a total of 36 TX-RX location combinations for the mobile (access) scenario and 38 combinations for the backhaul scenario. A pair of 27 dBi-gain rotatable directional horn antennas with a HPBW of 7° in both the azimuth and elevation planes was employed at the TX and RX. For each TX-RX location combination, TX and RX antenna azimuth sweeps were performed in steps of 8° or 10° at various elevation angles. Additional measurement procedures, hardware specifications, and channel modeling results can be found in [1], [2], [12], [13].

B. Indoor Measurements

During the summer of 2014, indoor propagation measurements at 28 GHz and 73 GHz were conducted on the 9th floor of 2 MetroTech Center in downtown Brooklyn, New York, using the same 400 Mcps broadband sliding correlator channel sounders described for the outdoor measurements, with slight differences. The main differences between the channel sounder systems were the TX output powers (lower for indoor measurements) and the use of widebeam TX and RX antennas indoors (15 dBi, 28.8° azimuth HPBW at 28 GHz, and 20 dBi, 15° azimuth HPBW at 73 GHz) [2]. The indoor environment consisted of a cubicle-farm layout with long corridors, hallways, and closed offices and labs. Five TX locations and 33 RX locations were used at 28 GHz and 73 GHz, resulting in 48 TX-RX location combinations measured for each band, with three-dimensional (3D) T-R separation distances ranging from 3.9 m to 45.9 m, where more than 14,000 PDPs were measured. Of the 48 identical combinations for 28 GHz and 73 GHz, 10 were for LOS and 38 were for non-line-of-sight (NLOS) environments. In order to emulate an indoor hotspot scenario, the TX antennas were placed 2.5 m high near the 2.7 m ceiling, and the RX antennas were placed 1.5 m above the floor (to imitate a human carrying a mobile device). Additional information can be found in [7].

III. LARGE-SCALE PATH LOSS MODELS

The five types of large-scale path loss models introduced in Section I are considered and compared using the outdoor and indoor data sets described above and detailed in [2], [7]. The equation for the single-frequency FI model is given by (1):

\[ \text{PL}^{\text{FI}}(d) [\text{dB}] = 10 \alpha \log_{10}(d) + \beta + \chi_{\sigma}^{\text{FI}}, \quad \text{where } d \geq 1 \text{ m} \]

where \( \text{PL}^{\text{FI}}(d) \) denotes the path loss in dB as a function of the 3D T-R separation distance \( d \), \( \alpha \) is a coefficient characterizing the dependence of path loss on distance, \( \beta \) is a floating intercept in dB, and \( \chi_{\sigma}^{\text{FI}} \) is the shadow fading (SF) standard deviation describing large-scale signal fluctuations about the mean path loss over distance. The FI model is used in the WINNER II and 3GPP channel models [8], [9], but it requires two model parameters \( (\alpha \text{ and } \beta) \) and does not consider a physically-based anchor to the transmitted power.

For the CI model, the equation is given by (2):

\[ \text{PL}^{\text{CI}}(f, d) [\text{dB}] = \text{FSPL}(f, 1 \text{ m}) [\text{dB}] + 10 n \log_{10}(d) + \chi_{\sigma}^{\text{CI}}, \quad \text{where } d \geq 1 \text{ m} \]

where \( n \) denotes the single model parameter, the path loss exponent (PLE), with \( 10 n \) describing path loss in dB in terms of decades of distances beginning at 1 m (making it very easy to compute power over distance), \( d \) is the 3D T-R separation distance, and \( \chi_{\sigma}^{\text{CI}} \) denotes the free space path loss in dB at a T-R separation distance of 1 m at the carrier frequency \( f \), where \( c \) is the speed of light. Note that the CI model has an intrinsic frequency dependence of path loss embedded within the 1 m FSPL value, and it has only one parameter, PLE, to be optimized. Furthermore, the CI model is applicable to both single- and multi-frequency cases. Free

\[ ^{1} \text{In some of our previous publications, } \alpha \text{ denoted the floating intercept and } \beta \text{ represented the distance coefficient. The two notations are swapped here to keep consistent with the notations in the ABG model given by Eq. (9).} \]
space path loss in the first meter of propagation ranges between 32 and 72 dB from 1 to 100 GHz, where a substantial amount of path loss in a practical mmWave communication system occurs. This first meter of loss is captured in the FSPL term, and is treated separately from the PLE which characterizes loss at distances greater than 1 m \[2\].

The ABG model aims to model large-scale path loss as a function of frequency as well as distance, and is expressed as follows:

$$PL^{ABG}(f, d) [dB] = 10\alpha \log_{10}\left(\frac{d}{1 \text{ m}}\right) + \beta + 10\gamma \log_{10}\left(\frac{f}{1 \text{ GHz}}\right) + \chi^{ABG}_s,$$\quad (3)

where \(PL^{ABG}(f, d)\) denotes the path loss in dB over frequency and distance, \(\alpha\) and \(\gamma\) are coefficients showing the dependence of path loss on distance and frequency, respectively, \(\beta\) is an optimized offset (floating) value for path loss in dB, \(f\) is the carrier frequency in GHz, and \(\chi^{ABG}_s\) is the SF standard deviation describing large-scale signal fluctuations. The coefficients \(\alpha\), \(\beta\), and \(\gamma\) are optimized from closed-form solutions that minimize the SF standard deviation \[7\].

The CIF model is given by Eq. (4)\[7\]:

$$PL^{CIF}(f, d) [dB] = \text{FSPL}(f, 1 \text{ m}) [dB] + 10n \left(1 + b\left(\frac{f - f_0}{f_0}\right)\right) \log_{10}(d) + \chi^{CIF}_s,$$

where \(d \geq 1 \text{ m}\) and \(f \geq 1 \text{ GHz}\).

IV. OUTDOOR PROPAGATION PATH LOSS RESULTS

Using the five large-scale propagation path loss models presented above and the outdoor measurement data at both 28 GHz and 73 GHz, path loss parameters are analyzed and compared. The single-frequency FI and CI model parameters at 28 GHz and 73 GHz for the UMi SC scenario are contained in Table \[1\] (for the purpose of comparing path loss models and saving space, only omnidirectional path loss data measured with vertically-polarized TX and RX antennas are included; information on directional path loss and other polarization scenarios, as well as published raw data can be found in \[2\], \[19\]). It can be observed from Table \[1\] that the CI model provides intuitive path loss model parameter values due to its physical basis, while the parameters in the FI model sometimes contradict fundamental principles. For example, for the UMi SC LOS environment at 73 GHz, the CI model generates a PLE of 2.0, which matches well with the theoretical free space PLE of 2; however, the \(\alpha\) in the FI model is -0.8, meaning that the path loss decreases with distance, which is obviously not reasonable or physically possible in a passive channel.
The path loss results for the UMi SC scenario using both the 28 GHz and 73 GHz outdoor measurements data sets for the multi-frequency ABG, CI, and CIF models are provided in Table I. As shown by Table I for the LOS environment, both the CI and CIF models provide a PLE or α of 2.0, which agrees very well with the theoretical free space PLE of 2. In contrast, the ABG model yields an α of 1.0, substantially lower than the theoretical free space PLE, indicating its lack of physical intuition. Meanwhile, the SF standard deviations for the ABG, CI, and CIF models are virtually identical, with a maximum difference of only 0.2 dB. The CIF model yields a value of \( n \) that is identical to the PLE in the CI model for the UMi SC scenario. The frequency term \( b \) in the CIF model is very small, i.e., -0.06 and -0.00 in LOS and NLOS environments, respectively, indicating that path loss has negligible frequency dependence beyond the first meter of propagation in UMi channels at mmWave frequencies, thus proving that the single-parameter CI model may be used for LOS and NLOS outdoor channels.

Table I

| Scen. | Env. | Freq. (GHz) | Dist. Range (m) | Model | \( \text{PLE}_{\text{LOS}} \) | \( \beta \) (dB) | \( \gamma \) (dB) | \( \sigma \) (dB) |
|-------|------|-------------|-----------------|-------|-------------------|----------------|----------------|--------------|
| UMi SC | LOS | 28          | 31-54           | FI     | 3.9               | 3.8            | 2.9            |              |
|        |      | 73          | 27-54           | CI     | 2.1               | 4.5            | 5.2            |              |
|        | NLOS | 28          | 61-186          | FI     | 2.0               | 4.9            | 4.9            |              |
|        |      | 73          | 48-190          | CI     | 3.4               | 9.7            | 9.7            |              |
| Indoor Office | LOS | 28          | 4.1-21.3        | FI     | 2.9               | 3.0            | 7.8            |              |
|        |      | 73          | 4.1-21.3        | CI     | 1.1               | 1.8            | 1.8            |              |
|        | NLOS | 28          | 3.9-45.9        | FI     | 3.5               | 7.1            | 9.7            |              |
|        |      | 73          | 3.9-41.9        | CI     | 3.2               | 9.6            | 11.3           |              |

V. Indoor Propagation Path Loss Results

In order to characterize co-polarization signal attenuation as a function of distance and frequency for the indoor office channel, the parameters for the single-frequency FI and CI models, and the multi-frequency ABG, CI, and CIF models are provided and compared, as previously published with raw data in [7]. The resulting single-frequency path loss model parameters emphasize the frequency dependence of indoor path loss beyond the first meter of FSPL, where PLEs at 73 GHz are larger than 28 GHz PLEs, as shown in Table I. Specifically, LOS PLEs are 1.1 and 1.3 at 28 GHz and 73 GHz, respectively, indicating constructive interference and waveguiding effects in LOS indoor channels at mmWave frequencies. Furthermore, the NLOS PLEs are 2.7 and 3.2 at 28 GHz and 73 GHz, respectively, showing that 73 GHz propagating waves attenuate by 5 dB more per decade of distance in the indoor environment beyond the first meter, as provided in Table I. The FI model indicates lower attenuation as a function of log-distance in some cases (73 GHz NLOS \( \alpha = 2.7 \) compared to \( n = 3.2 \), and 73 GHz LOS \( \alpha = 0.5 \) compared to \( n = 1.3 \)), however, the FI model parameters can exhibit strange, non-physics based values, specifically \( \alpha = 0.5 \) for 73 GHz LOS which implies ultra-low loss with distance (less than in a waveguide) that does not follow basic physics. The physically-based 1 m FSPL anchor of the CI model for single frequencies allows for a simpler model (only one parameter) with virtually no decrease in model accuracy (standard deviation of 9.3 dB and 9.6 dB for FI and CI, respectively in NLOS at 28 GHz, and 11.2 dB and 11.3 dB for FI and CI, respectively in NLOS at 73 GHz) by representing free space propagation close to the transmitting antenna.

The multi-frequency path loss models (ABG, CIF, and CI) allow for the comparison of distance and frequency dependence at the 28 GHz and 73 GHz mmWave bands in the indoor office environment. Figs. 1, 2, and 3 show the omnidirectional path loss data in LOS and NLOS environments at 28 GHz and 73 GHz and the corresponding multi-frequency model parameters and fits to the data, while the model parameters are also provided in Table I. Similar to the single-frequency CI model, the multi-frequency CI (still just one parameter) and CIF (only two parameters) models illustrate the physical basis via a free space reference distance at 1 m, while the CIF model includes a frequency-dependent balancing term \( b \). The added benefit of the frequency-dependent term in the CIF model is the improvement in model accuracy, i.e. reduction in standard deviation (2.3 dB (CI) compared to 2.1 dB (CIF) in LOS, and 10.9 dB (CI) compared to 10.4 dB (CIF) in NLOS), as the CIF model has a better fit to the indoor data than the CI model, inherent in the frequency dependence of path loss observed in indoor environments. The CI PLE and CIF \( n \) parameters are identical (1.2) in LOS and are extremely close (CI PLE of 2.9 and CIF \( n \) of 3.0) in NLOS, adding credence to their physical significance and stability. The ABG model (with three parameters) provides slightly lower standard deviations in both LOS and NLOS environments compared...
In Table II, it can be found that the magnitude of the path loss parameters between the UMi SC scenario and indoor office scenario is smaller for outdoor environments (0.18 and 0.21 for LOS and NLOS, respectively) than for indoor environments (2.9) than outdoor (3.4), which may be ascribed to waveguiding effects and more strong reflected paths in the indoor office environments.

VI. COMPARISON OF OUTDOOR AND INDOOR PATH LOSS RESULTS

By comparing the multi-frequency path loss model parameters between the UMi SC scenario and indoor office scenario in Table III, it can be found that the magnitude of $b$ in the CIF model is generally smaller for outdoor environments (-0.06 and -0.00 for LOS and NLOS, respectively) than for indoor environments (0.18 and 0.21 for LOS and NLOS, respectively), indicating less (in fact no frequency dependence whatsoever when $b=0$) frequency dependence of path loss in outdoor environments, beyond the first meter of free space propagation. The CIF model is quite similar to the CI model in terms of model parameters for outdoor environments and the extra frequency-dependent term of the CIF model is not needed, since the first meter of propagation captures virtually all of the frequency-dependent loss. We conclude that the CI model is thus most suitable for outdoor mmWave environments, as compared to the ABG and CIF models, while the CIF model is preferable to ABG and CI for indoor environments.

Furthermore, comparing the outdoor and indoor LOS PLEs for the multi-frequency CI model in Table III, it is observed that the outdoor LOS PLE (2.0) agrees well with the theoretical free space PLE of 2, whereas the indoor LOS PLE (1.2) is much lower than 2, due to waveguiding effects that enhance the received signal strength in indoor office environments. In addition, the NLOS multi-frequency PLE is also smaller for indoor environments (2.9) than outdoor (3.4), which may be ascribed to waveguiding effects and more strong reflected paths in the indoor office environments.

VII. CONCLUSION

This paper describes the mmWave propagation measurements in both UMi SC and indoor office scenarios at both 28 GHz and 73 GHz, and presents and compares the single-frequency FI and CI path loss models, as well as the multi-frequency ABG, CI, and CIF models, using the data from extensive measurement campaigns. Single-frequency path loss results show that the CI model is preferable compared to the FI model (presently used in WINNER and 3GPP) for both outdoor and indoor environments, due to its physical basis, simplicity, and robustness over measured frequencies and distance ranges. Multi-frequency analysis shows that the CI model is suitable for outdoor environments because of its physical basis, stability, simplicity, and the fact that measured path loss exhibits little dependence on frequency in outdoor environments, beyond the first meter of free space propagation (that is captured in the CI model). On the other hand, the CIF
model is well suited for indoor environments, since it is based on physics, requires only two parameters as a natural extension of the CI model, and incorporates the frequency dependence feature of path loss observed in indoor environments.

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