

Empirical Comparison of Propagation Models for Relay-Based Networks in Urban Environments

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ABSTRACT We investigate propagation characteristics for wireless channels, applicable to Integrated Access and Backhaul (IAB) and relay-based networks with lamppost-height nodes at 5.5 GHz. We compare our empirical results with a variety of models that have been proposed for system simulation. Our work is based on an extensive measurement campaign in an urban environment, where we simultaneously measured base-relay, relay-mobile and base-mobile links. This simultaneity allows us to conclude that low-height relay nodes offer a minor path-loss advantage over the base-user link. Moreover, within the range of relay heights that we measured of 2.8 and 4.7 m, we observed no significant gain associated with choosing the higher relay placement. Our results however also show that the base-relay link is quite stable over time and thus will lend itself to multi-antenna techniques requiring a small overhead in channel state information feedback. Our results add to the empirical data that the standards models are based on, providing path-loss results obtained simultaneously for all links of an urban relay-based system.

INDEX TERMS Channel models, integrated access and backhaul, 5G IAB, path loss, propagation, relay networks.

I. INTRODUCTION

The demand for high-speed wireless access continues to increase rapidly. As the radio spectrum becomes more crowded, new technologies must be developed to increase spectral efficiency. In this context, reducing the cell coverage area by limiting transmit power and using cooperative transmission schemes becomes an attractive solution to improve traffic density. Furthermore, new upper-layer services encompassing human-to-machine and machine-to-machine interaction (as virtual/amplified reality, tactile internet and Internet of Things (IoT) [1]–[3]) will require low or ultra low latency with extremely high availability, and reliability [4]–[6]. Relay-based networks, with lamppost-height

nodes, may be an attractive solution to improve the access infrastructure in these new use-cases, as well as in Vehicle to Vehicle (V2V), Vehicle to Infrastructure (V2I) and Unmanned Aerial Vehicles (UAV) communications, among others [7]–[17].

3GPP Release 16 (2020) includes Integrated Access and Backhaul (IAB, also known as 5G IAB) as a potentially cost-effective solution to improve coverage. IAB nodes, successors of 4G relays, employ wireless connectivity for both access and backhaul links without expensive fiber deployment [18]. According to [19], IAB nodes are currently being deployed commercially throughout the world both at sub-6 GHz and at mmWave frequencies. For the sub-6 GHz band, which suffers from serious spectrum resource shortage, both access and backhaul links are expected to employ the same frequency band [20].

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Current technologies, such as LTE-Advanced, aiming at peak data rates of up to 1 Gbit/s in the downlink [21], [22], also consider relaying nodes [12], [17], [23]–[25]. To support such rates, high bandwidths are required. Given the high cost of the licensed spectrum, and the existing congestion in the 2.4 GHz band, the attention has now shifted to unlicensed higher frequencies, for example those covering the range of 5.2 GHz - 5.9 GHz, considered for urban microcellular scenarios [7], [8], [16].

Relays receive a wireless signal from a source and forward it to a destination, which may be able to receive both, the signal from the source and from the relay. This is known as cooperative relaying. Its theoretical properties have been studied as early as the 1970s [26]. However, the study of its integration into cellular networks only gained attention some decades later [27]. Since then, it has been capturing considerable attention [28] and is still the object of much research [24], [29]–[31].

If relays are to be a cost-effective solution in dense urban areas, it is likely that they will be installed at relatively low height, typically below rooftops, at lamppost-height [32]. Since they are to operate in scattering-rich environments, that can only be characterized by statistical models, a crucial aspect to estimate performance is the joint distributions of path-losses for all the propagation channels involved. Validating models for these statistics is the main objective of this paper. Our findings are based on simultaneous measurements for Base-Relay (BS-RS), Base-Mobile (BS-MS) and Relay-Mobile (RS-MS) links in an urban environment, with lamppost-height relays at an operating frequency of 5.5 GHz. We note that for the simulation of relay networks, the typically suggested propagation models rely on empirical data that was not necessarily obtained in the same urban locations for each link [33]–[43]. In contrast, our measurements for all links correspond to a single urban region and thus when compared to each other, variations due to differences in the tested areas are excluded. Moreover, most models currently in use were not originally developed for relay systems, and in contrast to what we here report, are not based on data obtained simultaneously for the three links involved or even in the same urban locations. As pointed out in [44], joint statistics of the links, based on simultaneous measurements, are essential to properly assess the benefits of relaying.

Different standardization groups have proposed path-loss models for RS-MS links, applicable to Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) urban environments operating at 5.5 GHz. Among them: ITU-R Recommendation (P.1411-10) [45], WINNER II (D1.1.2 V1.2) [46], IEEE 802.16j (06/013r3) [47] and ITU-R M-2412 for IMT-2020 systems [48]. The empirical data supporting these models was in general collected under conditions different from the ones we considered in our work. For the WINNER II model closest to our case (“B5c” scenario for LOS and “B1” for NLOS), the RS-MS link involved one terminal at 8 m height and the

other on a vehicle at street level, with link lengths in excess of 60 m [49], [50]. The IEEE 802.16j recommendation is based on [51] for Type-F below rooftop LOS links, while for NLOS links the model is described in [52]. For the LOS case, measurements were carried out at 457.2 MHz and 10.7 GHz, with terminals at heights of 3 m and 24 m above street level. The ITU-R Recommendation also considers LOS and NLOS models. Their models for the LOS case match those described in [53] based on data obtained in a single 27 m wide street at frequencies of 3.35 GHz, 8.45 GHz and 15.75 GHz.

Some published models, while not aimed at relay systems, may be also adequate to predict channel losses for the RS-MS segment. For example, [54] proposes a model based on measurements at 5.3 GHz with heights of 2 to 3.5 m for base antenna and a height of 1.8 m for the remote antenna. However, the measurements are for sidewalk to street links, therefore ignoring obstacles and scattering that might be present in cross-street links such as trees or vehicles [55]. The measurements for residential areas reported in [56] also correspond to sidewalk to street links and do not consider the effect of traffic. In [57], a simulation tool for predicting signal level in urban environments is introduced, but validated only with measurements performed at 910 MHz.

Relay assisted systems have typically been simulated using some of the standardized models just described and thus the accuracy of the results hinges upon their correctness for the environment under consideration. Several simulations consider frequency bands in the same range of the one used in our work. For example, in [33] and [34] the WINNER II model is used for 3.95 and 5 GHz. An older model, the SCM-Extended model [58] is used in [35]–[39] for the simulation of a low-height relay at 5.8 GHz. Even simpler models have been used, such as the free space path-loss equation in [40]. In [41], a dense urban area Manhattan like scenario is analyzed, using an indoor 5 GHz path-loss model. Simple 2-slope models are considered in [42] without specific information on break-point location. Similarly, in [43], a two-slope model is used under the assumption that the path-loss exponents are 2 and 4.

Simultaneous measurements for all links involved in a relay-based system have been reported before, but they differ from the research presented here. In [44] and [59] measurements for indoor environments are reported. Outdoor measurements at 3.7 GHz performed at street level in Ilsan, Korea are described in [60]–[62]. This work however only deals with cross-correlation of fades in two coexisting channels and does not include path-loss comparison of the various links, as done in our work. Simultaneous measurements for relaying channels at 2.25 GHz in downtown Ottawa are reported in [63]. In this case both BS and RS antenna were placed at a 6 m height and the purpose was to determine the coverage improvement achieved by a nearby RS that would fill coverage gaps when the BS-MS link is obstructed by the high-rise construction. Street-level measurements on a moving vehicle at 3 locations were limited to ranges of no

more than 2 city blocks from BS or RS. In [64], similar measurements were reported, but focusing on the fast fading rather than path-loss as done in our work. In contrast to the above, our measurement campaign at 5.5 GHz considers a BS located 177 m above a downtown area in Viña del Mar, Chile, where we positioned the RS at 6 different locations and measured on 8 streets covering 32 city blocks. The area contains a mix of up to 60 m high buildings and some one- and two-story houses. Our purpose was to determine the potential gains of using low-height RSs to improve coverage over that achieved by the BS when transmitting directly to the MS.

Empirical results for relay links in settings similar to those we report in our work are described in [65]. However, the measurements at 2.35 GHz were not done simultaneously, and in contrast to our study, NLOS links are not included. This is a significant difference since for dense urban settings most user location are NLOS.

As follows from the above discussion, while models are being extensively used, there is still a lack of empirical data that can validate which are the most accurate for a given set of conditions, particularly based on simultaneous measurements of all links in a relay-assisted scheme. In addition, most models proposed for links with both terminals (relay and user) below the clutter, have not been formulated for the specific purpose of simulating low-height relay-based links, as done in our work. Furthermore, as will be discussed, there are differences among the path-loss predictions of various models, which suggest that relay system simulation will yield different results depending on the choice of model.

Our measurement campaign considers a below rooftop urban scenario using carriers in the 5.5 GHz band. We measured outdoor links involving relay positions on sidewalks close to buildings and trees at two different heights (2.8 m and 4.7 m). For user positions (MS) with a 1.6 m high antenna at sidewalk positions we measured path-loss simultaneously from the BS and the RS. At the same time we measured the BS-RS links using a macrocell base station at a 2 km distance. Our results thus exclude possible errors due to the combination of link models, particularly since even for nominally similar environments these exhibit significant differences among each other. In summary, the main contributions of the work we here report are:

- Assessment of the benefits obtainable from the use of lamppost-height relays in urban settings, using path-loss measurements obtained simultaneously for all links involved. This contrasts with most previous work where models for the links are based on measurements performed separately, often in different environments.
- Validation of path-loss models applicable to relay networks with bases below urban clutter, including the effect of possible correlations among links. This addresses the case where both RS and MS are below urban clutter, a condition for which there is



FIGURE 1. Measurement region.

little empirically based data, resulting in significant differences among models for nominally the same environment.

- Using our very extensive set of empirical data to verify which of the various published path-loss models best characterize the specific links involved in urban low-height relays.

II. MEASUREMENT PROCEDURE

A. EQUIPMENT SETUP AND DATA PROCESSING

We measured path-losses for the three links involved in a relay-assisted system using a continuous wave carrier at the BS and RS. These were offset by 8 MHz, which allowed the MS to receive both simultaneously. The RS was implemented using a Software Defined Radio (SDR), programmed to switch between transmission and reception modes. It alternates between a 20 ms transmission and a 0.73 ms reception interval. The latter is used to measure the static BS-RS link, which requires fewer measurements than the links involving the position-changing MS.

The BS consisted of a synthesized signal source and a power amplifier operating at 5.496 GHz. A power of 33.9 dBm was fed to the input terminal of a sector antenna with 90° half-power beamwidth and 14.8 dBi gain. The antenna was located in a clutter-free placement on a 177 m high hill overlooking the RS and MS positioning area at a range of 2 km as shown in fig. 1. The antenna tilt was chosen to maximize received power at a LOS position within the measurement area. We note however that virtually all MS and RS placements considered in our study were of NLOS type with respect to the BS, as this corresponds with realistic deployment scenarios.

The RS used a single monopole omnidirectional antenna for both modes, with a measured gain of -0.1 dBi. This antenna was located on top of a retractable mast that was adjusted to heights of 4.7 and 2.8 m. The 5.504 GHz signal transmitted by the RS had a power of 18.9 dBm at the antenna terminal. The RS equipment was mounted on a cart providing a stable antenna position, as shown in fig. 2. This cart allowed us to emulate a RS placed in positions similar to lampposts. The MS equipment was also mounted on a cart, but instead of



FIGURE 2. Carts used for measurements. On the left is the RS cart. On the right is the MS cart.

a mast, we built a handheld antenna unit that allowed a person to move in a range of 3 m without having to relocate the cart. This allowed collecting enough power samples at each cart location to average out small-scale spatial fades. The MS receiver consists of another SDR, but configured in reception mode only. The antenna used was a monopole having a measured -1.2 dBi gain. Receive preamplifiers were used to improve system noise figures. To measure power, the SDRs are configured for the 5.5 GHz frequency band and the down converted received signal is sampled and processed via Fast Fourier Transform (FFT) on a laptop computer to determine its amplitude. The interval between successive power samples was much smaller than the observed coherence times for the links, which allowed us to monitor equipment stability and to average FFTs to improve measurement accuracy. Our system was carefully calibrated to determine its capabilities, being able to measure path-losses of up to 159 dB in the BS-MS link, 155 dB in the BS-RS link and 139 dB in the RS-MS link, with received signals that are at least 6 dB above noise floor.

The measurement campaign involved positioning the RS at 6 locations at the two aforementioned heights. For each of them the MS was placed at 275 surrounding LOS and NLOS sidewalk positions within a few city blocks, as will be described below. At each MS placement the procedure involved capturing data while one person covers a 3 m distance, at a slowly walking pace during a 23 second interval. This resulted in observed coherence times for the BS-MS and the RS-MS links in excess of 100 ms. After FFT processing and averaging, we obtained 250 simultaneous power samples from the RS and BS during each such interval. The BS-RS link was observed to be very stable and thus the FFT amplitudes showed very little variation as will be discussed later. The power samples obtained at each MS position allowed spatial averaging over the 3 m range to



FIGURE 3. Relay stations deployment in Viña del Mar. For RS1 and RS2, MS covered the green area. For RS 3 and 4, MS covered the red area. For RS 5 and 6, MS covered the blue area.

isolate the small-scale from the shadow fades. As suggested in [66], covering a distance of 40λ (with λ being the carrier frequency wavelength) is enough for this purpose, a requirement met by our system. On the other hand, the distance traversed in each measurement is well within the coherence distance reported for similar environments [67]. Considering the 3 links involved, our full measurement campaign resulted in over 450,000 link measurements for each RS height.

B. DESCRIPTION OF TESTED SCENARIOS

We measured a relatively densely populated sector in downtown Viña del Mar, Chile, during daytime, over a period of several weeks. This area contains a mix of buildings with heights of up to 60 m and some one- and two-story houses. Streets are 10 m wide, with sidewalks adding 7 m. City blocks are 105 m long. Dense, slow-moving traffic includes automobiles in around 90% of cases, with the rest being mostly trucks and only occasional passing of passenger buses. Pedestrians are generally present but sidewalks are not crowded. Different types of trees, up to 6 m high, line the sidewalks. The city blocks form a square grid as shown in fig. 3. In this figure we also show the RS positions, marked as “RS i ”, $i = 1, 2, \dots, 6$ and the streets where the MS was positioned, which are highlighted in color.

We chose 3 specific blocks, in which the RS was positioned in the middle of the block and near one of its corners. At each placement, we installed the RS antenna at heights of 2.8 and at 4.7 m. Small changes in the RS position can significantly affect the small-scale fade value. We used a consistent procedure for all placements. Our initial choice was “corner of block” or “center of block”. For each case, we positioned the cart with the RS antenna in the chosen placement, and then moved it parallel to the street in a range of about 30 cm to avoid a deeply-faded position within that range. This would emulate an installation by a technician who rather than attaching a terminal at random, avoids a particularly poor choice due to a local fade. Our search was restricted to a small

range (30 cm) of feasible positions, as would for example be possible along a building wall chosen for this purpose. This search procedure took no more than 10 min, considering that the cost-effective deployment of relays should not entail a time-consuming search for particularly good locations. For each of these position-height combinations we measured simultaneously the BS-RS, BS-MS and RS-MS path-losses in the areas shown in fig. 3. Our measurements include distances that may extend well beyond the coverage range of a relay. This is justified by the fact that in modeling a relay system, one needs to consider the path-loss between relay and user as well as the interference caused by neighboring relays, which may be at a much larger distance from the user.

III. EMPIRICAL RESULTS

A. PATH-LOSSES FOR BS LINKS

We firstly present our results for the individual links from the BS to RS and to MS as a way of validating that our environment is consistent with those described by well-known models, including the classical Okumura-Hata and COST231-Hata models. The corresponding median path-losses are shown in Table 1. 90% of our observed values were found to be within ± 13 dB of the median. We note that the range of the various model-predicted and observed path-losses is quite large and that our scenario is more representative of the lowest reported values. Even though our setting corresponds to a fairly typical urban environment, we cannot claim validity to scenarios different to the type of environment where we measured. The wide range of variation among models is well known to occur, and as stated in [68], a path-loss prediction based on a model that is nominally similar to that of the measured environment can result in errors of up to ± 20 dB. This may require testing and adapting model parameters to tune it to the specific conditions of the scenario. In our case, the 2 km links were essentially unobstructed over most of the trajectory starting at the BS due to its antenna height and terrain topography. Construction-related blockages were only significant over the last 300 to 400 m. This may explain our relatively low path-losses. The quite small decrease in median path loss with antenna height (MS and RS) suggests that little gain can be expected from

TABLE 1. Comparison between empirical and model path-losses for BS-MS and BS-RS links.

Model	BS-MS	BS-RS 2.8m	BS-RS 4.7m
Empirical Median Value	134.5 dB	130.9 dB	130.7 dB
802.16j Type-E WI NLOS	168.8 dB	164.7 dB	158.2 dB
802.16j Type-E WINNER NLOS	154.8 dB	154.8 dB	154.8 dB
WINNER II - C2 NLOS	148.1 dB	148.1 dB	148.1 dB
WINNER II - B5f NLOS	N/A	136.0 dB	136.0 dB
ITU - ORT urban area	146.4 dB	146.0 dB	145.2 dB
IMT-Advanced - UMa NLOS	133.7 dB	131.6 dB	129.2 dB
Okumura - Hata	145.2 dB	143.0 dB	140.7 dB
COST231 - HATA	153.9 dB	151.7 dB	149.4 dB

this aspect alone. We note that both heights of the RS place it below urban clutter such as construction and trees, but above most passing vehicles. Thus the statistically insignificant decrease of 0.2 dB with antenna height is not unexpected. This will be treated in greater detail in Subsection C by comparing simultaneous measurements for matched pairs of BS-MS and BS-RS links.

B. RS-MS LINK

The path-loss values for all RS locations were separated into two groups, with RS heights of 2.8 and 4.7 m, respectively. In addition, we separated the data into “same-street” and “around-corner” links. For simplicity we henceforth refer to them as LOS and NLOS respectively, noting that in the former case some links include minor street clutter and vegetation. However such obstructions were relatively sparse and this simple classification showed a good fit to theoretical models for both LOS and NLOS cases. We here compare applicable RS-MS models against our measurements, after averaging out the small-scale fades.

We compare at each range the predicted model path-loss from the corresponding empirically obtained value. Since most models do not achieve a good fit with our data, the mean model error, i.e. the model-bias, is not zero. Additionally we calculate the Root Mean Square (RMS) error between the tested model and our empirical data, which will of course also depend on the model bias.

We have chosen for comparison a set of well-known path-loss models recommended by standardization groups, applicable to our tested scenarios and measurement configurations, i.e. Below Rooftop (BRT) transmissions for the RS-MS links. The models and the choice of their parameters is described in what follows.

1) LOS MODELS

From the IEEE 802.16j (06/013r3) recommendation [47], we use the Type-F LOS propagation models. Specifically, the Advanced LOS model (with visibility factor $s = 0.002$ and effective road height h_s of 1.0 m) and the alternative WINNER formula also presented therein for BRT-BRT links. We will refer them as 802.16j Type F - Advanced LOS and 802.16 Type F - WINNER LOS models, respectively. From the WINNER II project [46] we will use the B5c scenario, which represents a LOS static base, with BRT to street-level connections. This model will be denoted as WINNER II - B5c. From the IMT-Advanced [48] we chose the Urban Micro Model for LOS links (denoted as IMT-Advanced UMi - LOS). The effective road height, referred to in the document as “effective environment height”, is also assumed to be equal to 1.0 m.

The ITU-R Recommendation [45] also provides path-loss models applicable to the 5.5 GHz band. We used the recommended SHF propagation models for LOS links, which specify median, upper and lower bounds for losses. Our measurement conditions loosely correspond to what the document specifies as “heavy traffic”. For this

case the path-losses are reported to have no breakpoint although -despite its description- this is a two-slope model. In contrast with the preceding models however, the change in path-loss slope (i.e. the breakpoint) is specified to occur at a fixed distance (20 m) from the RS, independent of the RS height. We calculated the median and the bounds specified in the Recommendation. It is worth mentioning that [53], which describes the same empirical data as the ITU document for the LOS case, provides a somewhat different interpretation of the “no-breakpoint” condition. In that study, the lack of an observable breakpoint for mobile terminals at 1.6 m height is argued to be due primarily to pedestrian traffic, suggesting the use of a single slope model. Since the condition “heavy traffic”, pedestrian or automotive, is not a very precise with regard to what we observed during our campaign, we also tested the ITU model with a breakpoint corresponding to an effective road height h_s of 1.0 m, as reported in [46]–[48]. We refer to these two ITU models as “ITU-LOS-NB” and “ITU-LOS-B” respectively.

We also performed a linear-regression fit to our data, as described by (1).

$$PL(d)[dB] = \begin{cases} PL(d_{ref}) + 10n_1 \log_{10} \left(\frac{d}{d_{ref}} \right) & d_{ref} \leq d \leq d_{bp} \\ PL(d_{bp}) + 10n_2 \log_{10} \left(\frac{d}{d_{bp}} \right) & d > d_{bp} \end{cases} \quad (1)$$

where d_{ref} is the reference distance up to which we consider free-space path-loss, assumed to be 1 m, $PL(d_{ref}) = 20 \log_{10} (d_{ref})$, λ is the carrier frequency wavelength, n_1 and n_2 are the first and second path-loss slopes and d_{bp} is the breakpoint distance. For this model, we chose the slopes that minimize the RMS error. To be consistent with the standards models, we considered 3 cases. firstly we assumed a RS-height dependent breakpoint, which as in the aforementioned models is calculated using (2) [53]:

$$d_{bp} = 4 \frac{(h_b - h_s)(h_m - h_s)}{\lambda} \quad (2)$$

where h_b and h_m are the antenna terminal heights, h_s is the effective road height, which for consistency with the standards models was also chosen as 1.0 m. This results in breakpoints at 79.2 and 162.8 m for RS heights of 2.8 and 4.7 m respectively. As a second alternative we considered the model described by (1), but with a fixed (i.e. RS-height independent) breakpoint at 20 m, as specified in the ITU recommendation for $h_s = 1.6$ m and “heavy traffic”. Finally, we also considered a single-slope model as suggested in [53].

2) NLOS MODELS

From the IEEE 802.16j (06/013r3) recommendation [47], we tested the Type-F NLOS propagation models. The first one, based on a model by Berg [47], is based on the geometry of the environment. We set the “ ν factor” equal to 1.5 and q_{90} equal to 0.5, as indicated in [47]. The second is an alternative WINNER approximation. We will refer to these

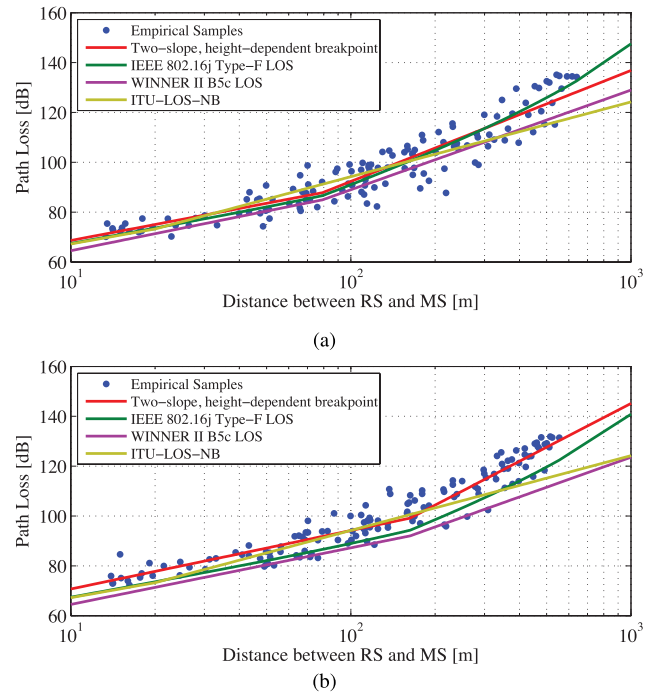


FIGURE 4. Comparison of empirical path-loss with models for the RS-MS link in the LOS case for (a) 2.8 m and (b) 4.7 m RS height.

models as 802.16j Type-F - Berg NLOS and 802.16j Type-F WINNER NLOS respectively. We also chose for comparison the B1 NLOS scenario reported by WINNER II channel models in [46] (denoted as WINNER II - B1 NLOS). The Urban Micro Model for NLOS links presented in [48] for IMT Advanced (denoted as IMT-Advanced UMi - NLOS) was also tested using a 1 m effective road height. From the ITU-R Recommendation we chose the model for propagation losses within street canyons for frequency range from 2 to 16 GHz [45]. Since in this model the path-loss is obtained by adding losses to those of the LOS path, we considered the same two cases previously described in the application of the LOS losses. The model considers the parameter values d_{corner} equal to 30 m, L_{corner} equal to 20 dB, β equal to 6 dB and our value of street width equal to 17 m.

Some of the aforementioned LOS/NLOS models were measured at frequencies different from 5.5 GHz. In such cases we applied a correction according to the path-loss frequency dependence modeled in [46].

3) EMPIRICAL RESULTS AND COMPARISON WITH MODELS

In fig. 4 (a) and (b) our LOS data is graphically compared with the models considering RS heights of 2.8 and 4.7 m, respectively. A summary of the results regarding model fit to our data is presented in Table 2, which also includes the parameters for the best fitting linear regression models.

To verify consistency of our results, we separated the data into sub-groups, one for each relay placement. We found that for both relay heights the corresponding points in the scatter-plots overlap, so we combined all into the sets shown

TABLE 2. Model accuracy for the RS-MS link in the LOS case.

Model	Mean Error		RMS Error	
	2.8m height	4.7m height	2.8m height	4.7m height
IEEE 802.16j Type-F LOS	0.2 dB	5.9 dB	5.9 dB	7.6 dB
IEEE 802.16j Type-F LOS WINNER	8.8 dB	11.3 dB	12.4 dB	13.8 dB
WINNER II B5c LOS	4.0 dB	9.2 dB	7.3 dB	10.9 dB
IMT-Advanced UMi LOS	4.2 dB	9.6 dB	7.4 dB	11.3 dB
ITU-LOS-NB	1.2 dB	3.6 dB	7.3 dB	7.1 dB
ITU-LOS-B	3.4 dB	9.1 dB	7.0 dB	11.0 dB
Two-slope model, height-dependent breakpoint	0.0 dB slopes 2.1, 4.6	-0.1 dB slopes 2.4, 5.8	5.9 dB	4.7 dB
Two-slope model, breakpoint at 20 m	0.0 dB slopes 1.7, 3.7	-0.1 dB slopes 1.9, 3.6	6.6 dB	5.6 dB
Single-slope model	-1.0 dB slope 2.5	-0.9 dB slope 2.6	8.3 dB	7.1 dB

in fig. 4. As seen from the graphs, although the models predict different average path-losses as a function of distance, the “cloud” of our measured values overlaps all model predictions, particularly for 2.8 m. Most of the models we considered report RMS errors of around 3 dB, which contrasts with the significantly larger dispersion of our measured values. Only the ITU - SHF LOS model specifies a relatively wide range of path-loss values through lower and upper bound curves. We found that at the RS height of 2.8 m, 77% of our measured values fall into that range when considering the “no-breakpoint” case and 87% do so for $h_s = 1$ m. For the RS height of 4.7 m the corresponding values are 86% and 71%.

Several conclusions follow from Table 2. The standards models that consider a height-dependent breakpoint exhibit a significantly better fit to our data at 2.8 m than to the data at 4.7 m. This is seen very clearly in the increase of mean errors (model bias) for the 4.7 m case. In particular, the IEEE 802.16j Type-F LOS model is quite accurate for 2.8 m, but does much worse at 4.7 m. We moreover found that if we use the 2.8 m model parameters with our empirical data for 4.7 m, the mean error drops from 5.9 dB to 2.4 dB and the RMS error decreases from 7.6 dB to 5.3 dB. When using this model with the aggregate measurements from both RS heights, the mean error is 1.3 dB and the RMS error 5.6 dB. In the same context, the ITU model with a fixed breakpoint at 20 m provides a similar match to our data at both heights, a further indication that the reduction in path-loss with RS height predicted by some models is not backed up by our measurements.

The two-slope models fitted to our data provide the best match, although the breakpoints (calculated from (2)) are quite different. A reduction of the breakpoint distance to only 20 m or the elimination of the second slope clearly impairs accuracy, as seen from the increase in RMS error. However, the latter two models again indicate that almost the same set of parameters characterize our measurements at both heights. We note that the path-loss prediction of the models depends on the position of the breakpoint, which as a result of (2) varies with RS height. As will be described below, we instead found that our data does not point to a precisely

defined breakpoint position as a function of RS height. This may be the result of the random variability of traffic density, which affects the value of h_s and as discussed in [53], due to pedestrian traffic, which causes blockages not affected by the RS height. Using (2) we also find that for reflection on an empty street ($h_s = 0$) the breakpoint distance is 329 m when the RS is at 2.8 m, which decreases to 9.5 m if the reflection occurs on a car surface at 1.5 m height ($h_s = 1.5$ m). Given the random nature of traffic and thus the random occurrence of such conditions, this may explain why no well-defined breakpoint distance characterized a best-fit model for the large collection of measured positions. To investigate this point we optimized our models using three degrees of freedom, one breakpoint and two slopes. We found that a good fit to data can be achieved over a wide range of parameter combinations. We varied the assumed breakpoint position in the range of 20 to 160 m considering the data at 2.8 and 4.7 m and calculated the best-fit slopes and the model errors. The results are shown in fig. 5. As seen, the modeling errors exhibit a very broad minimum at around 100 m in both cases. Moreover, the resulting best-fit slopes, which vary considerably with the assumed breakpoint position, remain very similar for both RS heights. This confirms that a single model is adequate for both RS heights. When combining all data, we confirmed that the exact location of the breakpoint had little effect. The choice of 100 m results in a mean error of 0.0 dB and an RMS error equal to 5.4 dB, which is almost the same error as obtained for the aggregate data when using the IEEE 802.16j Type-F LOS model with parameters for 2.8 m. The corresponding path-loss slopes are 2.2 and 4.9, which are values consistent with those in the standards models. Our empirical data suggests that there is no significant improvement in RS-MS path-loss when the RS is elevated from 2.8 to 4.7 m. Regarding the path-loss model, the inclusion of a break point clearly improves model accuracy over the single-slope fit, as expected from more adjustable parameters.

In the same way, we compared NLOS models with our empirical data. The reference NLOS models consider path-loss equations involving the LOS distance (d_1), the “around the corner” distance (d_2), and finally, some of them include d_3 , which is another “around the corner” distance as shown in fig. 6. Since it cannot be assumed a-priori that received power is negligible after the first corner, we considered it important to measure around the second corner to the extent of our system’s capabilities, considering that signals from neighboring relays, even when subject to high path-losses, can lead to the accumulation of unacceptable levels of user interference [69]–[71]. Among the models considered, the 802.16j Type-F - Berg NLOS is the only one of which includes d_3 in its equations. Therefore the comparison of this model with our empirical data is based on our complete set of NLOS measurements, which includes 24 locations with two street corners. For the rest of the models, the comparison could only include data acquired within one corner distance. Comparing NLOS measurements with

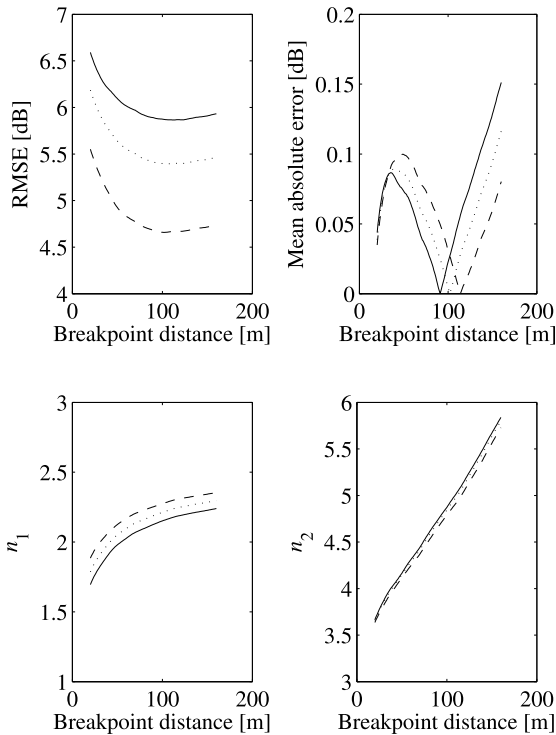


FIGURE 5. Best fit model parameters and RMS/Mean errors for base antenna heights of 2.8m (solid lines, -), 4.7 m (dashed lines, -) and aggregated data (both heights, dotted lines, ...).

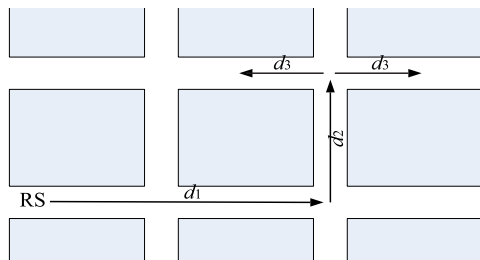


FIGURE 6. Definition of d_1 , d_2 and d_3 distances.

models through 3D figures using d_1 and d_2 results in cluttered graphs so we preferred to use two-dimensional graphs, where we plotted path-loss against the “Manhattan Distance” $d_1 + d_2 + d_3$ [72].

Table 3 summarizes model prediction errors. Since in the ITU case the total path-loss is a function of the losses in the LOS portion (d_1) we included both options considered for the LOS case, which we denote as “ITU-NLOS-NB” and “ITU-NLOS-B”. Figs. 7 and 8 show results for the 2.8 m RS position, considering two different models. Fig. 7 is based on all of our NLOS measurements, compared to the 802.16j Type-F - Berg NLOS model (for one and two corners), while fig. 8 considers the ITU-NLOS-NB model which proved to be the best model when only one street corner data is considered, as shown in Table 3 (with mean error of -0.8 dB and RMS error of 4.6 dB).

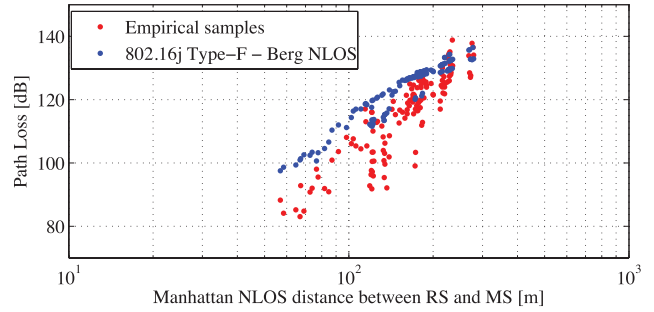


FIGURE 7. Comparison of path-loss for the RS-MS link in NLOS case. Includes measurements around one and two corners, i.e. non-zero d_3 distance.

As in the LOS case, we found that our empirical path-loss measurements on average showed very little variation when the RS height is increased from 2.8 to 4.7 m. This is seen in the table, when comparing the fit at both heights for the 802.16j Type-F - Berg NLOS and the ITU-NLOS-NB models, which are height-independent within the range of our measurements. Both exhibit similar errors for our two sets of data points. In the case of the ITU model, the fit is remarkably good, although unfortunately this model lacks expressions that include d_3 . In contrast, for the remaining models, which depend on RS height, the quality of the fit varies. The standard deviation for some of the models considered is specified to be close to 4 dB, comparable to the RMS error for the best fitting ITU model. Due to its LOS portion, the ITU models specify upper and lower bounds for path-loss, which we found to include about 90% of our measured values.

C. STATISTICAL COMPARISON OF THE BS-MS AND BS-RS LINKS

1) PATH-LOSS

We present a statistically-based comparison of the measured path-losses for the BS-MS and BS-RS links, noting that both are essentially of the same length and thus differences are only due to blockages and multipath. The comparison is important because the BS must first feed the RS with the information that is to be subsequently retransmitted to the user. If the BS-RS link does not allow much faster transmission to the relay than directly to the user, then the time expended in feeding the relay may actually result in worse performance than a direct transmission to the user. Increased data rate can be the result of reduced path-loss and thus a better Signal to Noise plus Interference Ratio (SINR) or of exploiting the static nature of the BS-RS link to achieve additional throughput, for example with the use of multiple antennas.

From the simultaneously measured BS-RS and BS-MS links for both RS heights we generate the Cumulative Distribution Functions (CDFs) of the dB difference in path-losses. We note that in this case we obtain the statistics of the path-loss advantage for the RS based on all instantiations of the measured link pairs rather than only the ensemble-average

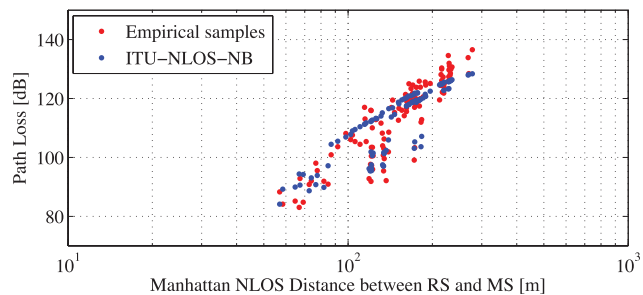


FIGURE 8. Comparison of path-loss for the RS-MS link in NLOS case. Includes measurements around one corner only, i.e. zero d_3 distance.

TABLE 3. Model accuracy for the RS-MS link in the NLOS case.

Model	Data included	Mean Model Error		RMS Error	
		2.8m height	4.7m height	2.8m height	4.7m height
802.16j Type-F - Berg NLOS	up to d_2	-8.7 dB	-7.9 dB	10.0 dB	9.3 dB
	up to d_3	-7.7 dB	-7.3 dB	9.5 dB	8.9 dB
802.16j Type-F - WINNER NLOS	up to d_2	-4.1 dB	-3.3dB	6.8 dB	6.2 dB
WINNER II - B1 NLOS	up to d_2	-4.8 dB	-2.3 dB	6.3 dB	4.9 dB
ITU-NLOS-NB	up to d_2	-0.8 dB	0.0 dB	4.6 dB	4.3 dB
ITU-NLOS-B	up to d_2	3.6 dB	6.6 dB	5.7 dB	8.4 dB
IMT-Advanced - UMi NLOS	up to d_2	-4.5 dB	-1.8 dB	6.1 dB	4.7 dB

advantage as listed in Table 1. The results are shown in fig. 9. We present the path-loss difference statistics when small-scale fades are included as well as when at each MS placement they are eliminated through spatial averaging. The latter case is representative for wideband links, where local multipath is averaged over a frequency range much larger than the coherence bandwidth. As seen, there is only a slight median path-loss advantage for the BS-RS links, about 1.3 dB for the case where small-scale fades have been averaged out. This increases to about 4 dB for the narrowband case. This behavior can be modeled by considering the origin and nature of the fades. For each placement the power received by the RS is essentially constant while the spatial displacement of the MS results in both shadow and multipath fades. The former are well described by a log-normal distribution for environments such as we tested and the latter are typically Rice/Rayleigh distributed with very low K -factors. Thus, the path-loss difference between RS and MS should be well modeled by a log-normal distribution for the case where power is averaged and a Rice/Rayleigh distribution with log-normal distributed average power for the narrowband case. This was indeed found to be the case as shown in fig. 9 where we show the fit of log-normal and log-normal combined with Rice CDFs. For the Ricean distribution we considered random log-normal distributed K -factors with average 0.4 resulting in 90% of K -factors below 0.8, which matched our data as discussed in Subsection 2. The offset of the CDFs from zero represents the median path-loss advantage of the RS due to its increased height.

We observed no statistically significant advantage associated with the increase of the RS height from 2.8 to 4.7 m.

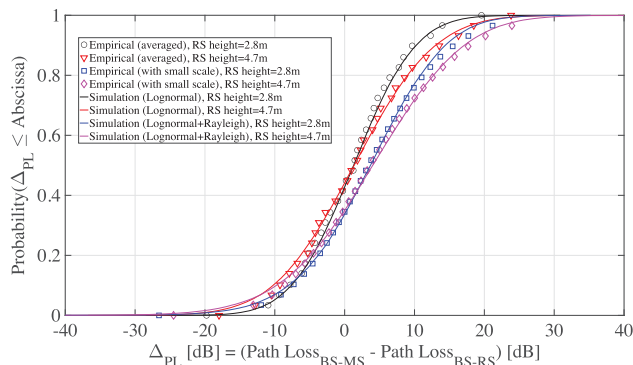


FIGURE 9. Comparison of empirical path-losses for the BS-MS and BS-RS links.

While at first sight this may seem surprising, we note that raising a terminal from 2.8 m to 4.7 m will only reduce path-loss if caused by blocking elements exceeding 2.8 m but lower than 4.7 m. However much of the higher urban clutter such as trees, will exceed both 2.8 m and 4.7 m and furthermore not diminish in width. Thus once the propagation path clears street level clutter such as cars and pedestrians affecting the 1.6 m high MS antenna, further path-loss reduction can only be expected when raising the RS above the height of treetops, utility posts and other similar objects. Further evidence of the effect of foliated treetops is the somewhat greater temporal variations observed for the 4.7 m high RS, as described in Subsection 2.

It follows from our observations that the small increases in received power by the RS with respect to the MS cannot be relied upon to obtain benefits from the use of relays. To achieve the much higher speeds required for the BS-RS link, other link features need to be exploited. This may include using multi-antenna systems that due to size constraints are not practical for a MS, as well as taking advantage of the higher stability of the BS-RS link, which will allow more complex modulation schemes than possible for the BS-MS link.

2) LINK STABILITY

Our measurements involved acquiring data sequences long enough to evaluate spatial and temporal fades. To this effect we considered the power samples obtained in the 23-second segments during which we moved the MS at each placement. Not surprisingly, the BS-MS and the RS-MS links showed (spatial) fades that are well characterized by Rice/Rayleigh distributions, with quite low K -factors. We found that for 90% of our time records, the K -factor did not exceed 0.8. In contrast, the BS-RS link proved to be much more stable over the same intervals. Temporal fades were very well characterized by a Rician distribution, and K -factors were as expected much higher. We found that for the relay at 2.8 m height, 90% of the K -factors exceeded 44. Somewhat surprisingly, at the 4.7 m height this value dropped to 17, presumably because the higher placement often resulted in closer proximity of the RS antenna to foliated tree-tops. Since

the path-loss advantage of the BS-RS over the BS-MS link is very modest, a higher transmission rate for the former may need to rely mostly on its improved stability.

3) FADE CORRELATIONS

The effectiveness of a relay-assisted link will depend on the ability of the relay to provide an adequate signal to the MS when high BS-MS path-loss is affecting the communication. A BS signal outage may be due to excessive link distance to the MS or to local fades. If at the cell edges, where the BS signal becomes too weak for reliable transmission to the MS, a relay is still able to adequately communicate with the BS (for example through use of more antennas than practical in a MS), then the relay can extend the cell coverage area. We will not deal with this aspect here. On the other hand, a position-related local fade of the BS signal inside the cell coverage area can be compensated by a stronger RS signal. Correlation of fades affecting the BS-MS and RS-MS links are not relevant if the average power received from either the BS or the RS are dominant [73], but must be considered if they are comparable. Therefore we calculated the correlation of the fades in these two links and for this purpose chose to treat shadow fades and small-scale fades separately. We first calculated small-scale fade correlation. To this effect we subtracted for both links the local average power and correlated the resulting differences. We repeated this for over 500 different 23-second time segments. As was to be expected, correlation coefficients proved to be very low, in fact within the uncertainty resulting from limited data sets, the correlation was equal to zero. Correlation was calculated for power in dBm or in Watts with similar results. While small-scale fade correlation was expected to be zero, this may not be obvious for shadow fades, which originate in large obstructions that could be common to both links. To calculate this correlation we considered the path-losses after averaging out small-scale fades. Thus in this case our data set is smaller. For the BS-MS link the range is almost constant, so we considered the average power over all locations and subtracted that to obtain the shadow fade for this link. On the other hand for the RS-MS link the average power is position dependent. In this case we chose our fitted two-slope model in the LOS case and the ITU-SC NLOS model for the NLOS case to subtract the average. The resulting correlations were again found to be very low, less than 0.1 for both cases. According to these results, the fades in both links may be considered uncorrelated.

Our results on the modest path-loss advantage achievable from low-height relaying bases are in line with accepted channel models, but in contrast with previous results, they have been validated by simultaneous measurements of all links involved in an actual urban relaying scenario and thus include the possible effects of correlation, which could not be ruled out a-priori. Our results also include channel stability, which is an additional relevant factor in determining the achievable data rates for the links and thus for the potential gains in throughput to the user terminal.

IV. CONCLUSION

We collected a large amount of measurements for the path-losses of the links involved in a relay-based network, such as those in 5G IAB at sub-6 GHz bands or in 3GPP LTE-Advanced. Our measured results, collected simultaneously for all links in a common setting, allow us to quantify and compare all path-losses, including the effect of changing the relay height from 2.8 to 4.7 m.

Our results show that a relay node can provide significant coverage, even if it is placed at low heights (2.8 or 4.7 m). This is relevant for the installation of high-speed cellular architectures, in areas that will be covered (densely) by small cells to improve system capacity. We found that a relay placed at lamppost-heights cannot be expected to have a statistically very significant path-loss advantage over a street-level user terminal. This matches the prediction of some of the standards models, although the median path-losses differ considerably among such models. Moreover, our BS-RS measurements showed virtually no path-loss gain associated with the increase in relay height from 2.8 and 4.7 m (130.9 dB for 2.8 m vs. 130.7 dB for 4.7 m, as shown in Table 1). We did however observe that the BS-RS links are relatively stable with (temporal) Ricean K -factors that typically were higher than 13 dB. This is important as a stable link can offer the advantage of allowing complex modulation schemes and also reduces the need for frequent channel state information updates, allowing efficient implementation of high-speed multi-antenna transmission schemes in the BS-RS link.

With regard to the RS-MS links, we found again that our data suggests no statistically significant advantage associated with the increase in relay height from 2.8 to 4.7 m (with measured path losses ranging from $\sim 70 - 140$ dB for link lengths between 10-1000 m in both cases, as shown in fig. 4). The reason for this may again be attributed to the fact that at both heights the relay remains within the same type of street clutter. Both in the LOS and the NLOS cases, we found that our data only fits with equal accuracy those models that are height-independent. For LOS links, a two-slope model can achieve a significantly better fit to our data than one with only a single-slope. However, we found that over a wide range of distances, the exact position of the breakpoint has little effect on model fit, which may explain the discrepancies among standards models on this aspect.

We finally also found that there is no evidence of path-loss correlation among links, which allows treating fades affecting the BS-MS and RS-MS as independent random variables.

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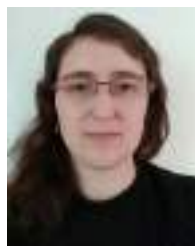
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