Path Loss Models for LTE and LTE-A Relay Stations

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Abstract Relaying technology is an essential part of 3GPP LTE-Advanced (3rd Generation Partnership Project Long Term Evolution - Advanced). This paper evaluates the path loss encountered on the backhaul link of relaying systems. The evaluation is based on an extensive measurements performed in 1900 MHz frequency band. The validity of different propagation models for multiple relay antenna heights is examined. The results of the analysis reveal that the applicability of commonly advocated models for relaying environment is still questionable. Some modifications of the original forms of the discussed models are introduced to make their predictions more reliable. With the proposed modifications, the analyzed models show good agreement with measurements. The prediction error is smaller than 0.37 dB, on average, and the accuracy ranges from 2.23 to 6.40 dB.

Keywords LTE-Advanced, 3GPP, WINNER B5f, IEEE802.16j, COST231-Hata, Lee Model, Path Loss Prediction, Relay Antenna Height Correction Factor

1. Introduction

The number of mobile cell phone users is increasing at the rapid pace. The annual growth of data traffic is estimated to remain high. The global mobile data traffic is expected to increase at the rate of 66 % from 2012 to 2017. The number of mobile-connected devices is expected to exceed the world population by the end of 2013 as reported in [1]. Thus, there is a need for wireless access systems that can accommodate such growth. Currently, Long Term Evolution (LTE) and LTE-Advanced are being rolled out by many operators to meet ever increasing demand for higher data rate.

Relay deployment, which is an integral part of LTE-Advanced, is used to enhance capacity, extend cell coverage area and increase the overall throughput of the network [2-4]. Relaying technology has been considered as one of the advanced features of LTE-Advanced. Relays are integral part of the next generation of mobile broadband communication systems [5, 6]. Moreover, relays are expected to be a viable cost efficient solution for replacement of base stations [7, 8].

One of the requirements for successful deployment of relay stations in cellular networks is the understanding of network coverage areas. Prediction of the path loss is a fundamental task in cellular systems deployment. To accomplish this task, engineers rely on propagation modeling that estimates the average signal strength and consequently the path loss on the link between a base station (i.e. eNodeB) and a relay station.

There is a number of relay propagation models. They have been suggested by 3GPP [4], WINNER (Wireless World Initiative New Radio) [9] and IEEE 802.16j task group [10]. However, models in [4] and [9] were derived for only one level of relay antenna height, namely 5 m and 15 m respectively, and therefore their applicability for multiple relay heights still needs to be studied. To the best of author's knowledge, very view studies evaluate the path loss on the eNodeB-relay link for different relay heights. The study in [11] investigates the impact of the relay height in WINNER models. Results of [11] show a mismatch between measurements and WINNER B5f model. Reference [12] proposes a new propagation model for multiple relay heights and discusses the validity of some existing models. Nevertheless, the new proposed model was suggested just for urban areas. Additionally, studies presented in [11, 12] conclude that the validity of the investigated models which were designed for relaying systems is questionable. Therefore, further studies are required to examine the validity of propagation models in relay based scenarios. Another work is reported in [13]; however, the maximum examined relay height is limited to 5 meters. These heights are considered to be low for most relay scenarios according to [4] and [9]. The research in [14] describes and documents measurement campaign which was set up specifically to examine the path loss on eNodeB-relay link. Even though an empirical propagation model for relaying scenarios is proposed, the study does not provide any comparison with other existing models.

When deployed, a multihop relaying system consists of two links. The first link is the link between the eNodeB and the relay and it is referred to as the backhaul link. The second link is the link between the relay and the end user and it is referred to as the access link. The study presented in this paper focuses on the path loss encountered on eNodeB-relay

link only. The validity of different propagation models is examined by comparing their predictions with measurements. Additionally, since many propagation models are already coded and are part of software packages it is of special interest to establish a relationship between measurements and some of these standard propagation models. Well known examples of the standard models are: Hata-Okumura, Lee model, COST 231-Hata, COST 231 Walfisch-Ikegami, and many proprietary models. Application of standard models for modeling relay scenarios is handled through addition of appropriate correction factors.

This paper is organized as follows. Section 2 gives an overview of measurement setup. In Section 3, some commonly used propagation models are reviewed. Section 4 presents the analysis of the obtained results, their comparison with existing models, evaluation of the path loss variability, differences between measurements and predictions and introduction of correction factors. Finally, a brief summary and conclusions are provided in section 5.

2. Experimental Setup

The experimental data collected for this study are obtained in a typical suburban area of Melbourne, FL, USA. The measurements were performed in 1900 MHz band which is one of the operating bands for the LTE-Advanced. Un-modulated carrier was transmitted from the roof of a 25.5-meter high building. The measurements were performed for multiple relay heights ranging from 4 to 16 m. Figure 1 illustrates the measurement system. Details of parameters associated with the measurements campaign and measurement procedure description are to be found in [14].

3. Relay Link Radio Propagation Models

In this section, a number of propagation models is presented. First three models were specifically developed for relaying deployment. Then, two of most widely used propagation models for planning of cellular networks are introduced and their performance in relaying scenarios is assessed.

3.1. 3GPP Model

Third Generation Partnership Project suggests several propagation models for predicting path loss at 2 GHz band [4]. Among the suggested models there is a model dedicated to eNodeB-relay links. For non-line of sight scenarios, the path loss is given as:

$$PL_{3GPP} = 125.2 + 36.3 \log(d) \qquad (1)$$

where d in [km] is the eNodeB-relay separation.

3.2. WINNER B5f Model

B5f model was developed by IST-WINNER II project [9]. WINNER models cover a wide range of propagation scenarios. Path loss models for the various WINNER scenarios have been developed based on measurements conducted within WINNER, as well as results obtained from the open literature. Among considered scenarios is the path loss model for fixed relays (i.e., stationary feeders), namely the scenario B5. This scenario is further divided into five sub-scenarios according to the relay location as it illustrated in Table 1. Based on [9], WINNER B5f sub-scenario is the most appropriate channel model for prediction of the path loss on the link between base station (i.e. eNodeB) and relay station. WINNER B5f model takes into account both LOS and NLOS conditions where the base station antenna height is above the rooftop level and the relay station antenna height is either above or below the rooftop level.
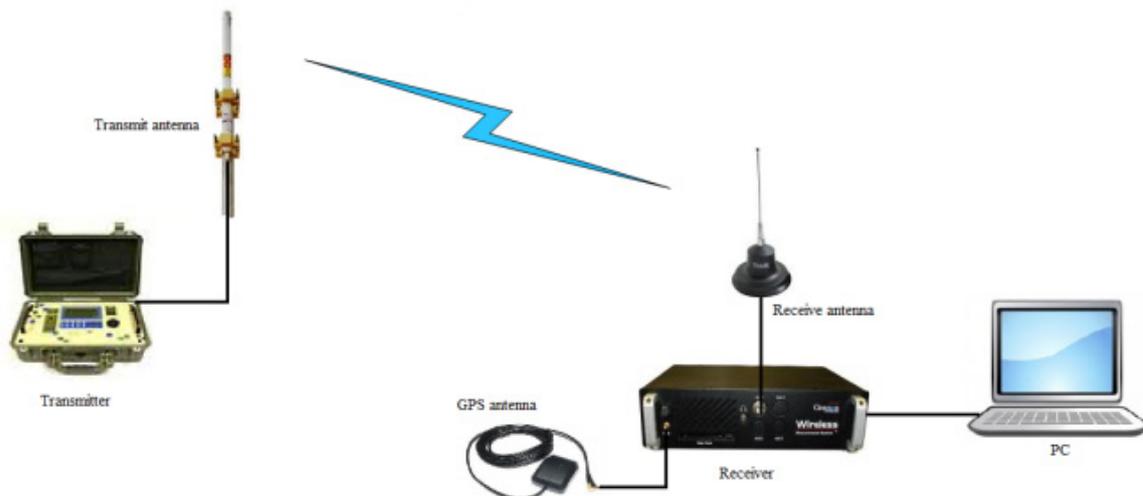

Figure 1. Illustration of the measurement system

Table 1. Sub-Scenarios of WINNER B5 model

Sub-scenario	LOS/NLOS	eNodeB location	Relay location
B5a	LOS	Above rooftop	Above rooftop
B5b	LOS	Street level	Street level
B5c	LOS	Below rooftop	Street level
B5d	NLOS	Above rooftop	Street level
B5f	LOS/NLOS	Above rooftop	Below/above rooftop

WINNER B5f model is given by:

$$PL_{WINNER} = 57.5 + 23.5 \log(d) + 23 \log\left(\frac{f}{5}\right) \quad (2)$$

where d in [m] is the distance (30 m $< d <$ 1.5 km) and f in [GHz] is the frequency (2 GHz $< f <$ 6 GHz).

3.3. IEEE802.16j Model

This model is based on SUI (Stanford University Interim) model and was developed in 2007 by IEEE802.16 Relay Task Group. The model covers relay scenarios in IEEE 802.16j WiMAX systems. The SUI model [15] is based on extensive field measurements collected at 1.9 GHz across the United States in 95 macro cells. The model was mainly derived for suburban areas with three most common terrain types, namely A, B and C. Type A describes areas which are hilly with moderate-to-heavy tree densities, and it is associated the maximum path loss. Type C applies to areas which are mostly flat with light tree densities and it has the smallest path loss. Type B has a moderate path loss and it represents either hilly terrains with light tree densities or mostly flat terrains with modest to heavy tree densities. In 2007, IEEE802.16 Relay Task Group developed the SUI model and introduced the IEEE802.16j model to cover nine categories of path loss for relay systems [10]. The categories are defined according to terrain type and location of the transmitter and receiver relative to the surrounding buildings. These categories are described in Table 2.

Table 2. Path loss types for IEEE802.16j relay system

Category	Description	LOS/NLOS
Type A	Macro-cell suburban, ART to BRT for hilly terrain with moderate-to-heavy tree densities.	LOS/NLOS
Type B	Macro-cell suburban, ART to BRT for intermediate path-loss condition	LOS/NLOS
Type C	Macro-cell suburban, ART to BRT for flat terrain with light tree densities	LOS/NLOS
Type D	Macro-cell suburban, ART to ART	LOS
Type E	Macro-cell, urban, ART to BRT	NLOS
Type F	Urban or suburban, BRT to BRT	LOS/NLOS
Type G	Indoor Office	LOS/NLOS
Type H	Macro-cell, urban, ART to ART	LOS
Type J	Outdoor to indoor	NLOS

Note: ART (Above Roof Top), BRT (Below Roof Top)

The IEEE802.16j path loss model for types A/B/C is given in [10] and it may be expressed as:

$$PL_{IEEE} = A + 10\gamma \log\left(\frac{d}{d_0}\right) + \Delta PL_f + \Delta PL_h + s \quad (3)$$

where $d > d_0$, d in [m] and $d_0 = 100$ m. The other parameter are defined as:

$$A = 20 \log\left(\frac{4\pi d_0'}{\lambda}\right) \quad (4)$$

$$d_0' = d_0 \, 10^{-\left(\frac{\Delta PL_f + \Delta PL_h}{10\gamma}\right)} \quad (5)$$

$$\gamma = a - bh_b + \frac{c}{h_b} \quad (6)$$

$$\Delta PL_f [\text{dB}] = 6 \log\left(\frac{f}{2000}\right) \quad (7)$$

$$\Delta PL_h [\text{dB}] = \begin{cases} -10 \log\left(\frac{h_r}{3}\right) & \text{for } h_r \leq 3 \\ -20 \log\left(\frac{h_r}{3}\right) & \text{for } 3 < h_r < 10 \end{cases} \quad (8)$$

where λ is the wavelength in [m], γ is the path loss exponent, f is the operating frequency in [MHz], h_r is the receiving antenna height in [m], h_b is the base station antenna height in [m], ΔPL_f is the correction factor for the frequency in [dB] and ΔPL_h is the correction factor for the receiver antenna height in [dB]. The parameter (s) in (3) represents the shadowing effect and it has a lognormal distribution. a, b and c are constants and they depend on the terrain type as provided in Table 3.

Table 3. Parameters for the terrain type A/B/C

Model parameter	Terrain A	Terrain B	Terrain C
a	4.6	4	3.6
b [m^{-1}]	0.0075	0.0065	0.005
c [m]	12.6	17.1	20

3.4. COST 231-Hata Model

The European Co-operative for Scientific and Technical research (EURO-COST) established the COST-231 working committee to introduce COST-231 model which is considered as an extended version of Hata model to frequencies up to 2 GHz. The model is widely used for prediction of the median path loss in mobile wireless systems and its formula is given by [16]:

$$PL_{COST231-Hata} = A + B \log(d) + C_m - a(h_m) \quad (9)$$

$$A = 46.3 + 33.9 \log(f) - 13.82 \log(h_b) \quad (10)$$

$$B = 44.9 - 6.55 \log(h_b) \quad (11)$$

where f is the frequency in [MHz], h_b, h_m are the transmitter antenna height and the receiver antenna height in [m], respectively, d denotes the transmitter-receiver separation in [km]. $a(h_m)$ is the receiver antenna height correction factor and is given as following.

For small to medium cities:

$$a(h_m) = (1.1 \log(f) - 0.7)h_m - (1.56 \log(f) - 0.8) \quad (12)$$

For large cities:

$$a(h_m) = \begin{cases} 8.29(\log(1.54 h_m))^2 - 1.1 \, , \, f \leq 200 \text{ MHz} \\ 3.2(\log(11.75 h_m))^2 - 4.97 \, , \, f \geq 400 \text{ MHz} \end{cases} \quad (13)$$

C_m is the environment correction factor and it is 0 dB for medium sized city and suburban areas and 3 dB for metropolitan centers.

3.5. Lee Model

Lee model is one of the most popular and widely used path loss models. It is known for its simplicity along with its reasonable prediction accuracy [17]. Lee model was initially derived for frequencies around 900 MHz. Later on, the model was extended to frequencies up to 2 GHz [17]. The path loss form of the model is provided relative to reference conditions and is given as [18]:

$$PL_{Lee} = PL_0 + m\log\left(\frac{d}{d_0}\right) - H_T - H_R \quad (14)$$

where:

$$H_T = 15\log\left(\frac{h_t}{h_{tref}}\right)$$

$$H_R = 10\log\left(\frac{h_r}{h_{rref}}\right)$$

and

PL_0 - Path loss at reference distance (d_0) in [dB]
m - Slope in [dB/decade]
d - Transmitter-receiver separation in [km]
d_0 - Reference distance (1.609 km)
h_t - Transmitter antenna height in [m]
h_{tref} - Reference transmitter antenna height (30.48 m)
h_r - Receiver antenna height in [m]
h_{rref} - Reference receiver antenna height (3.048 m)

The intercept (PL_0) and the slope (m) for different environments at 900 MHz are provided in Table 4.

Table 4.   Intercept and slope values for different environments

PL_0 @ f_0=900 MHz	PL_0 [dB]	m [dB/decade]
Open area	95	43.5
Suburban	107.7	38.4
Urban (Philadelphia)	116	36.8
Urban (Newark)	110	43.1

Whereas the slope (m) remains the same for frequencies different than f_0, frequency correction factor for the intercept (PL_0) is given by:

$$PL_0(f) = PL_0(f_0) + 20\log\left(\frac{f}{f_0}\right) \quad (15)$$

Each individual propagation model has its own set of assumptions and is restricted to a specific range of parameters under which it was derived. When a propagation model is used to predict path loss outside of the specified parameter range, its validity becomes questionable. Table 5 summarizes the range of parameters under which the previously mentioned propagation models were derived.

Table 5.   Models' parameters and corresponding assumptions

Model	f [GHz]	Tx antenna height [m]	Rx antenna height [m]	d [km]
3GPP	2	30	5	NS
WINNER B5f	2-6	25	15	0.03-1.5
IEEE802.16j	2-11	10-80	3-10	0.1-8
COST231-Hata	1.5-2	30-200	1-10	1-20
Lee	0.850-2	20-100	1-15	up to 20

4. Results and Discussion

This section analyzes and evaluates the behavior of mentioned propagation models with respect to the field measurements reported in [14]. These measurements were performed at 1925 MHz in suburban environment.

4.1. Performance Evaluation of Existing Models

The validity of models is examined by comparing their path loss prediction to the measurements. While no particular parameters for 3GPP and WINNER B5f models need to be defined, following assumptions were made for the other three models in this study. In the case of IEEE802.16j model, terrain type "B" was considered the most suitable one for the environment in which the measurements were collected. Moreover, "suburban environment" category with receive antenna height correction factor $a(h_m)$ for small to medium city was used for the case of COST231-Hata model. Finally, corresponding values of slope and intercept for "suburban area" were assumed for the case of Lee model.

Figures 2 to 5 show the path loss predictions of the existing models for different relay antenna heights (h), namely 4, 8, 12 and 16 m, along with the measurements versus the distance between the eNodeB and the relay station.
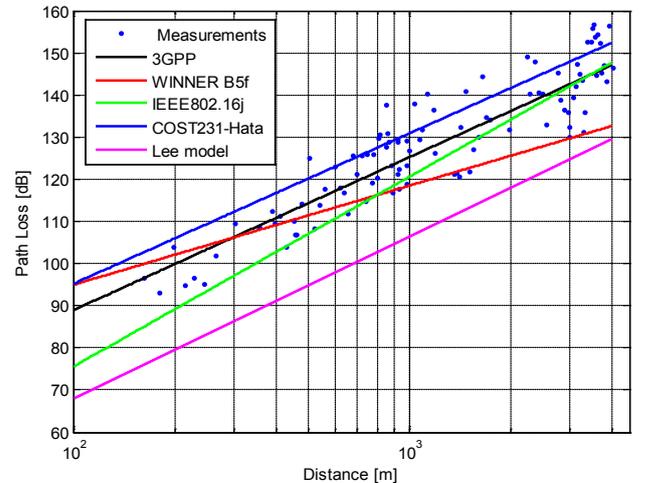

Figure 2.   Comparison of model predictions with measurements for h=4 m
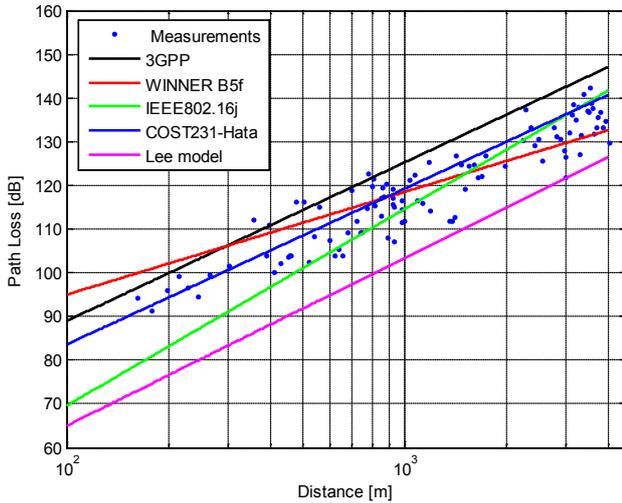
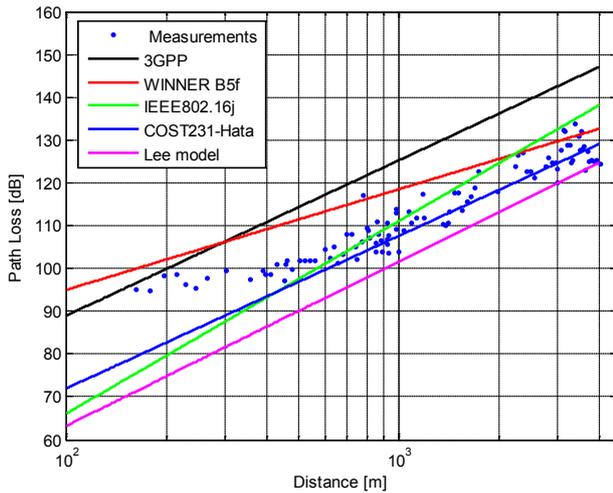**Figure 3.** Comparison of model predictions with measurements for *h*=8 m

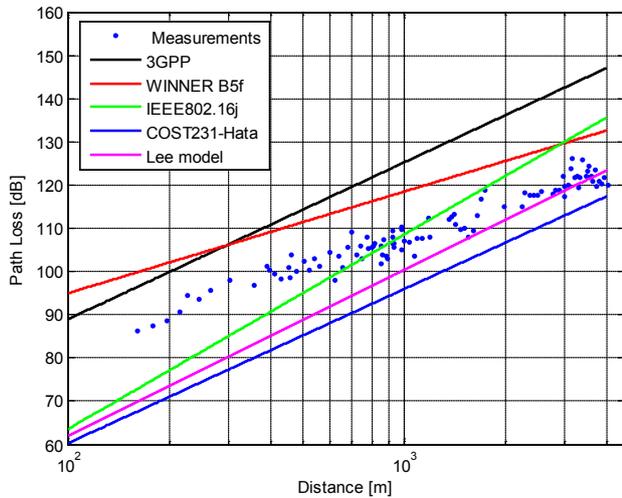**Figure 4.** Comparison of model predictions with measurements for *h*=12 m

Figure 5. Comparison of model predictions with measurements for *h*=16 m

One general observation from Figures 2 to 5 is that the path loss is a linear function of the log of the distance. Another observation is that there is a clear trend of decreasing path loss values with the increase of the relay antenna height. The trend is observed for the measurements and all five models except for 3GPP and WINNER B5f models. These two models were developed just for fixed relay heights and therefore they do not have antenna height correction factors. As a result, path loss predictions made by those two models remain the same for all relay heights.

Even though graphs give general understanding on how a propagation model behaves compared to measurements, statistical analysis provides more information about the accuracy of model predictions. The metrics used for the evaluation of propagation models are the mean of the prediction error (μ) and the standard deviation (σ) of this error. The prediction errors are defined as the difference between model predictions and the measurements. One should note that σ is used to indicate the accuracy of model predictions. To this end, Table 6 compares the results obtained for different propagation models relative to the measurements.

It is noteworthy to point out that a positive value of μ of a model means that the model on average over estimates the path loss value, i.e. the model is pessimistic. Negative values indicate that the predicted path loss is smaller than expected. Likewise, a small value of σ indicates a good model prediction, while a large value demonstrates lower model's accuracy.

As Table 6 shows, while for h = 8, 12 and 16 3GPP model significantly over predicts the path loss values, the model matches the measurements with very small μ of 0.54 dB for h=4. This result may be explained by the fact that 3GPP model was developed under assumptions similar to the h=4 case presented in this study. The 3GPP model was developed for frequency of 2GHz, base station antenna height of 30 m and relay height of 5 m. On the other hand, the lack of relay antenna height correction factor of 3GPP model for heights different than 4 m leads to the mismatch between the model with measurements in the cases of h =8, 12 and 16 m. The model accuracy ranges from 4.81 to 6.37 dB.

Table 6. Comparison between measurements and models' predictions

Model	Metric [dB]	Relay height (*h*) in [m]			
		4	8	12	16
3GPP	μ	-0.54	8.54	14.7	17.91
	σ	6.37	5.00	4.55	4.81
WINNER B5f	μ	-8.08	1.00	7.17	10.38
	σ	8.34	5.50	3.85	2.28
IEEE802.16j	μ	-4.65	-1.59	1.05	1.76
	σ	6.83	6.86	7.10	7.82
COST231-Hata	μ	5.07	2.50	-2.99	-11.43
	σ	6.40	4.92	4.40	4.61
Lee	μ	-19.28	-13.21	-8.81	-6.85
	σ	6.34	5.33	5.09	5.52

Consider now WINNER B5f model. It is clear from Figure 5 (h=16 m) that if model predictions had been shifted down by some value, they would have followed the measurements. According to Table 6, this shift is 10.38 dB which is the mean of the prediction error. Except for this shift, there is an agreement between the model predictions and the measurements with very small standard deviation of 2.28 dB. This may be explained by similarity in the assumptions between measurements and WINNER B5f model. It seems possible that the model over estimates the actual path loss values by 10.38 dB, on average, since WINNER B5f model was designed for urban environments and not for suburban ones. Similar to 3GPP model, WINNER B5f model was developed for a certain level of relay height and does not provide an antenna height correction factor. The standard deviation of prediction error (σ) is greater than 8 dB for h=4 m. Therefore, model predictions for other relay heights are not reliable.

Unlike the 3GGP and WINNER B5f models, IEEE802.16j model has a correction factor for the relay height which was expressed in (8). Nevertheless, the model predictions are incoherent with the measurements. This incoherence is pronounced and can be easily seen for the higher levels of relay heights (Figure 4 and Figure 5). Quantitatively, this is also clear since σ is relatively large and more than 7 dB for relay heights greater than 12 m. This is because the model is not valid for relay heights greater than 10 m. For relay heights 4 and 8 m, the model underestimates the actual path loss especially for distances closer to the transmitter (Figure 2 and Figure 3). The average error for h=4 m is 4.65 dB.

Even though both COST231-Hata and Lee models provide receive antenna height correction factors, their predictions, in general, are not in a good agreement with the measurements. While, in the case of COST231-Hata, the model over predicts the path loss for lower relay heights, its underestimation is noticeable for higher relay heights. This mismatch with the measurements is due the fact that COST231-Hata model does not take the clutter and terrain profile into account. In addition, the model is an extension version of Hata model which was developed in Japanese and European cities which in turn have different clutter and terrain profile than US cities. In the case of Lee model, the model seems to be very optimistic in predicting the path loss. The prediction error exceeds 19 dB for lower relay heights.

4.2. Relationship between Measurements and Existing Models

Propagation modeling tools are used for design of cellular networks. These tools include some widely used propagation models which are already coded and used for path loss predictions. Some well-known examples are COST231-Hata model and Lee model. These models were developed for path loss prediction between the base station and mobile stations. As a result, as it was shown in the previous section, their applicability for eNodeB-relay link does not seem to be appropriate.

In an attempt to make these coded models applicable in relaying scenarios, some modifications of their original forms are introduced. The modifications are based on an attempt to make these models follow the measurements with small prediction errors and high prediction accuracy for relay heights ranging from 4 to 16 m.

For COST231-Hata model, the modified version of the model is given as:

$$PL_{mod\ COST231-Hata} = A + B\log(d) - \Delta h - 12.56 \quad (16)$$

where A, B and d are the same as they were defined for the original model. Δh is the relay antenna height correction factor and it is given by [14]:

$$\Delta h[\text{dB}] = \left[22\log\left(\frac{d}{d_0}\right) + 7.47\right]\log\left(\frac{h}{4}\right) \quad (17)$$

where h is the relay antenna height in meters, d in meters is the separation between the eNodeB and the relay, and d_0 is equal to 100 m. Note that the difference between the original model and the modified version is the following. The term C_m, in the original form of COST231-Hata model given in (9), was omitted since its values is equal to zero for suburban environments. Also the receiver height correction factor $a(h_m)$ was replaced by a new one Δh. Finally, an adjusting factor of 12.56 dB was added to the modified version of the model.

In the case of Lee model, the modified version is given by:

$$PL_{mod\ Lee} = PL_0 + m\log\left(\frac{d}{d_0}\right) - H_T - \Delta h - 28.38 \quad (18)$$

The model parameters are identical to those of the original Lee model except for the value of d_0. The reference distance (d_0) is now equal to 100 meters instead of 1 mile (or 1.609 km). The reference distance is changed since it is quite common to deploy relays at hundreds of meters from the base station. Δh is defined as in (17). Comparing (14) and (18), one can see that the receive antenna height correction factor has been replaced and a new adjusting factor of 28.38 dB has been added.

For 3GPP and WINNER B5f models, which were suggested to be used in relay scenarios, are now expanded by introducing a relay antenna height correction factor. One should keep in mind that these models were derived for just one level of relay antenna height. The introduction of the relay antenna height correction factor will make these models applicable for multiple relay antenna heights. The modified version of 3GPP model is given as:

$$PL_{mod\ 3GPP} = PL_{3GPP} - \Delta h + 0.38 \quad (19)$$

where PL_{3GPP} is the predicted path loss calculated by the original 3GPP model, and Δh is defined as in (17).

The modified version of WINNER B5f model is given by:

$$PL_{mod\ WINNER} = PL_{WINNER} - \Delta h_W - 10.66 \quad (20)$$

where PL_{WINNER} is the path loss prediction made by the original WINNER B5f model. Note that Δh_W is slightly different than Δh for other models, and it is given as:

$$\Delta h_W[\text{dB}] = \left[22\log\left(\frac{d}{d_0}\right) + 7.47\right]\log\left(\frac{h}{16}\right) \quad (21)$$

It is noteworthy to point out that the modified versions of 3GPP and WINNER B5f models are developed by just adding the appropriate adjusting and relay antenna height correction factors to the original forms.

Finally, for IEEE802.16j model, it should be noticed that the applicable range of the receive antenna height was limited to 10 m. ΔPL_h given by (8) for IEEE802.16j model is modified so that the model can be used to predict the path loss in relay scenarios even when h greater than 10 m. The modified version of IEEE802.16j model is now given by:

$$PL_{mod\ IEEE} = A + 10\gamma \log\left(\frac{d}{d_0}\right) + \Delta PL_f - \Delta h_I \quad (22)$$

where the modified-model parameters are the same as for the original one except for Δh_I which is now given as:

$$\Delta h_I[\text{dB}] = \left[6.8 \log\left(\frac{d}{d_0}\right) - 9.21\right] + \Delta h \quad (23)$$

The introduction of the correction factors to the existing models achieves two main goals. Firstly, 3GPP, WINNER B5f and IEEE802.16j models are now applicable for multiple relay heights. Additionally, COS231-Hata and Lee models are now expanded into relaying propagation scenarios.

Table 7 provides the final comparison between the extended versions of the considered models and the measurements. The comparison is made in terms of the mean (μ) and the standard deviation (σ) of the prediction error.

Table 7. Comparison between measurements and models' predictions after correction factors implementation

Model	Metric [dB]	Relay height (h) in [m]			
		4	8	12	16
3GPP	μ	-0.16	-0.37	0.37	-0.28
	σ	6.37	4.70	3.54	2.32
WINNER B5f	μ	-0.16	-0.37	0.36	-0.28
	σ	6.36	4.68	3.50	2.28
IEEE802.16j	μ	-0.16	-0.37	0.36	-0.28
	σ	6.34	4.65	3.43	2.23
COST231-Hata	μ	-0.16	-0.36	0.37	-0.27
	σ	6.40	4.73	3.61	2.39
Lee	μ	-0.15	-0.36	0.37	-0.27
	σ	6.34	4.66	3.43	2.23

Table 7 clearly shows that the path loss predictions of all discussed models correspond with the measurements, on the average. It is also obvious that μ and σ are almost the same for all models and relay heights. For all models, μ is smaller than 0.37 dB, on the average. Note that σ represents model's accuracy and it ranges from 2.23 to 6.40 dB. These data are in a good agreement with the results reported in [14]. Note that σ is getting smaller as the relay antenna goes higher. This is because the path loss variations (shadowing effects) decrease as the link between the transmitter and the receiver becomes clearer.

It can be concluded that it is possible to make all considered models perform adequately in relying scenarios and with approximately the same accuracy. The modified models can be used to predict the path loss in the backhaul link of relaying systems in 1900 MHz band for distances up to 4 km and within environment similar to the one in which the measurements were conducted.

5. Summary and Conclusions

This paper evaluated the behavior of some existing propagation models in relaying scenarios. The study focused on the path loss predictions in the backhaul link only. The study examined the path loss for multiple relay heights in a suburban environment. Four levels of relay antenna heights ranging from 4 m to 16 m with 4 m step were examined. Performance evaluation of existing models was based on measurements campaign conducted in 1900 MHz frequency band. Five propagation models namely, 3GPP, WINNER B5f, IEEE802.16j, COST231-Hata and Lee model have been investigated. Even though 3GPP, WINNER B5f and IEEE802.16j models were designed for relaying systems, results show that the applicability of these models is not completely appropriate for multi relay antenna height scenarios. Moreover, in the case of Lee model, the prediction error is larger than 19 dB. Therefore, appropriate correction factors were added to their original forms to make all these models suitable for different heights of the relay. After modifications, for all models, the accuracy ranges from 2.23 dB for higher relay heights (~16m) to 6.40 dB for smaller ones (~4m). All models work with the same accuracy and with negligible mean prediction errors (less than 0.37 dB on average). It is concluded that with proper correction factors, all models examined in the study perform adequately and with similar accuracy.

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