Experimental Results For the Propagation of Outdoor IEEE802.11 Links

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***Abstract*—WiFi-based Long Distance (WiLD) networks have emerged as a promising alternative technology approach for providing Internet in rural areas. An important factor in network planning of these wireless networks is estimating the path loss. In this work, we present various propagation models we found suitable for point-to-point (P2P) operation in the WiFi frequency bands. We conducted outdoor experiments with commercial off-the-shelf (COTS) hardware in our testbed made of 7 different long-distance links ranging from 450 m to 10.3 km and a mobile measurement station. We found that for short links with omni-directional antennas ground-reflection is a measurable phenomenon. For longer links, we show that either FSPL or the Longley-Rice model provides accurate results for certain links. We conclude that a good site survey is needed to exclude influences not included in the propagation models.**

***Index Terms*—WiLD, Long-Distance WiFi, IEEE802.11, Propagation, Two-Ray, Directional Antenna, Longley-Rice**

I. Introduction

A major problem for rural areas is inaccessibility to affordable broadband Internet connections. While areas with Internet access benefit from its possibilities, areas that do not have this technology will fall behind even more. This may force companies and people into a difficult decision: whether to leave a specific region or stay behind and hope for better connectivity. Rural areas often have attributes that lead to high Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) for Internet Service Providers (ISPs). Therefore to decrease the costs of backhauling in rural regions, various alternatives are evaluated to establish high-bandwidth connections. One of these alternatives is WiFi-based Long Distance (WiLD). WiFi-based Long Distance (WiLD) networks consist of multiple wireless links spanning over long distances between 1 and 50 km using high-gain directional antennas and IEEE802.11 COTS hardware. Given their distribution in the consumer sector, the radios used are well developed, sold at a decent charge, have a low energy consumption and perform solidly in the license free Industrial, Scientific and Medical (ISM) or Unlicensed National Information Infrastructure (U-NII) band.

It is generally desirable to achieve a maximum amount of throughput for wireless connections. This involves the usage of high-order Modulation and Coding Scheme (MCS) for WiLD links. The major constraint for the physical rate of WiLDs is the Signal-to-Noise ratio (SNR) needed for these high-order MCS. To accomplish the network planning process and monitor propagation issues, a model is preferable that accurately describes the path loss in WiLD networks. Combined with the precise throughput and delay modeling presented in [1], this model provides Wireless Internet Service Providers (WISPs) with a means of comprehensively evaluating the performance in advance.

In comparison to models concealing wide areas supposing point-to-multipoint connections, the context of WiLD facilitates this issue to a propagation between two outdoor antennas. A structured verification of these modeles in conjunction with WiLD has not been found yet. This work addresses this issue by dealing with the following research questions:

- Which propagation models can be used for outdoor IEEE802.11 links?
- Is it possible to utilize Free and Open-Source Software (FOSS) to model these links accurately?
- Can the influence of environmental factors on path attenuation be measured?

II. Previous Work

In [2], the authors argue that it is acceptable for WiLD to model the propagation attenuation with the fundamental and well-known concept Free-Space Path Loss (FSPL) since the direct ray is the only significant contribution to the received signal. However, they also describe that in some cases this assumption does not hold, and instead they suggest using statistical model.

A major limitation when applying the FSPL model is the required antenna height on the transmitter and the receiver side [3]. For low antenna heights in relation to the distance, the earth curvature and Fresnel zones are significant issues.[3] has proposed a method for calculating the path loss for Line-of-Sight (LoS) WiFi links, which has been compared with existing previous models such as FSPL, Hata and Lee, and was also validated in experimental measurements. It takes the Fresnel zone into account and provides accurate performance for links with antenna heights between 1 and 2.5 m.

The measurements in [4] were conducted with antennas mounted onto cars in a flat desert environment. In this particular environment, the main advantage is the lack of interference from other WiFi transmitters influencing the results. The distance was increased by the authors up to 7 km over flat terrain. Surprisingly, and despite the fact that the Hata model [5] is not defined in the frequency band they used (2.4 GHz), measured and predicted values correlated well.

In [6] various aspects for packet loss in WiLD were characterized by the authors. They also found that multi-path interference causing Inter-symbol Interference (ISI) is not an issue for long-distance links, which is particularly interesting from the propagation perspective. In such scenarios, reflections on long distances primarily occur from the ground instead from buildings or obstacles as they do in urban regions. The authors concluded that two factors reduced the delay spread compared to urban deployments. First, the LoS path is assumed to have significantly more received signal strength than the reflected rays due to the directional characteristic of the antennas. Second, while the link-distance increases, the difference in the path length of the LoS and reflected component decreases since both components travel nearly the same way. Similar results have been achieved in a semi-urban link in [7].

In [8] there are substantial propagation measurements for various long-distance links presented by the authors. They concluded that the Received Signal Strength (RSS) variation for links on land is only between 1-2 dB. However, the authors measured a variation of 20 dB for a 19 km link at sea, their variation depends greatly on the tidal level of the sea. In fact, the work showed that the signal strength variation at sea can be predicted by using a simple two-ray reflection model. The direct path between the two directional antennas and the possible reflected ray from the ground, in this case the surface of the ocean, are taken into account in this model. Because of the differences in the individual path lengths, changes to the phase and the amplitude[1] of the signal occur at the receiver. Similar results have been obtained in [9] when a plane was flying on different routes above the sea. The predictions for the RSS made by the two-ray model are significantly more accurate than those by the FSPL equation.

In [10] the diffraction loss in a rural broadband scenario has been modeled using deterministic modeling techniques and generated terrain profiles. This technique provides information whether there are obstructions in the first Fresnel zone or not. The obstructions are approximated as knife edges and additional path loss is calculated.

According to [2], the Longley-Rice model seems to be a promising candidate for an accurate propagation prediction. However, an appropriate terrain profile needs to be acquired for all links under consideration [11]. In addition, [3] finds that the Longley-Rice model seems only to be defined for link distances longer than one kilometer, which imposes some limitations to an universal solution for WiLD connections.

Several studies were published regarding the influence of different weather conditions on WiLD links with varying results. For instance, [12] depicts that neither rain nor fog has a noticeable influence ($\approx 1-2dB$) on a 5 km link operating at 2.4 GHz. However, [13] achieved completely different results. Multiple environmental factors such as relative humidity, wind speeds, temperature, rainfall and its density are considered by the authors and the effects to the throughput measurements on a 300 m link were observed. The authors concluded that the throughput on the link was significantly reduced due to rainfall.

[1]Due to constructive and destructive interference.

III. Radio Propagation Models for outdoor links in the ISM and U-NII band

Radio propagation models have been a research topic for decades. They are used by network planers and designers to calculate the signal coverage of a wireless network. There are models for indoor usage to calculate the coverage of an 802.11 WiFi infrastructure or for outdoor models to forecast the possible size of network cells. The authors in [3] describe that widely used propagation models are not suitable for WiLD links. The Okumura [14] and Hata [5] models are mainly used in large urban-macro cell. In addition, they are specified for a frequency band of 150-1500 MHz and antenna heights above 30 m. The same limitation is valid for the COST231-Hata model, which is only specified up to 2000 MHz and is therefore not applicable in the 2.4 GHz ISM and 5 GHz U-NII band.

In the following, we described different propagation models we found suitable for outdoor (long-distance) P2P links operating either in the ISM or U-NII band.

A. Free space propagation model and Fresnel zones

The Free-Space Loss (FSL) is a well-known concept for describing the propagation of electromagnetic waves without considering effects caused by obstacles such as reflection or diffraction, simplifying signal propagation in many aspects.

The IEEE defines Free Space Loss as "The loss between two isotropic radiators in free space, expressed as a power ratio" [15],[16]. This loss does not occur due to dissipation, but due to the fact that power density decreases with the square of the separation.

Fresnel zones are another basic concept. As described in [17], the Fresnel zone is "the concept of diffraction loss as a function of the path difference around an obstruction". Fresnel zones represent regions where the path length of the secondary waves is $n\lambda/2$ greater than the LoS path. Additional attenuation occurs if some of these secondary paths are blocked due to obstructions, leading to a situation where only a portion of the overall energy is diffracted around the obstructive objective. As a rule of thumb, this effect is negligible if less than 55% of the first Fresnel zone is blocked [17]. As described in [17], accurately quantifying additional loss due to obstacles in the Fresnel zone is a complex mathematical problem since the loss depends on the shape, size and material of the obstacle.

B. Two-Ray model

Even without direct obstruction of the LoS or the Fresnel zones, additional attenuation can affect the received power. Multi-Path propagation can lead to destructive (and constructive) interference at the receiver. A common multi-path source for outdoor links is the ground itself. A well-known model describing this effect is the so-called two-ray path loss model [17]. In this model, two rays of electromagnetic waves are considered to arrive at the receiver with a certain phase and amplitude difference. The phase difference mainly depends on the additional propagation time of the ground-reflected wave compared to the direct LoS path. In addition, the model takes the ratio between absorbed and reflected energy on the ground into account. This ratio depends on the angle of incidence, the polarization of the wave and ground-related parameters such as the conductivity and the relative permittivity. A complete mathematical description is available in [17].

C. Longley-Rice

The Longley-Rice radio propagation model is also known as the Irregular Terrain Model (ITM) and describes the prediction of radio signal attenuation. Initially it was used for television broadcasting signals, but it can also be applied in our use-case because of its wide frequency spectrum (20 MHz to 40 GHz). Using electromagnetic theory and statistics on terrain conditions and radio measurements (the model is therefore empirical), it is able to depict the attenuation of a signal alongside a communication link. The Longley-Rice model also deals with the effects of ground reflections similar to the Two-Ray model. One of the main difference compared to the FSPL and the Two-Ray model is that Longley-Rice deals with diffraction. For further information about the model, the reader is referred to [18].

IV. Methodology

This section describes our methodology for analyzing the predictability of the path loss for outdoor IEEE802.11 links. It deals with describing the FOSS framework we use for applying the path analysis, our long-distance WiFi testbed, link budget calculations and the hardware and software used to obtain the results.

A. SPLAT!

SPLAT! is an abbreviation for 'Signal Propagation, Loss And Terrain' and contains a Linux-based open-source tool for different RF analysis of the electromagnetic spectrum above 20 MHz. Therefore it is an excellent testing environment for analyzing WiFi-based networks. Based on digital elevation topography models recorded by satellites, this tool can create visualizations and link budgets calculations for Wide Area Networks (WANs). These are calculated by different location files filled with the longitude and latitude parameters of an antenna site. Additionally the height above ground level of the antenna cam be included. SPLAT! is able to analyze and visualize the properties of P2P links between antenna sites and delivers results for the condition of the Fresnel zone, the attenuation alongside the connection and the received signal strength on the receiver site. Also it is able to recommend the height levels for the antenna sites in case there are obstructions in the direct LoS between transmitter and receiver of the considered link.

B. Rhein-Sieg testbed

The Rhein-Sieg testbed is an already deployed WiLD in the Rhein-Sieg area around the Fraunhofer Institutes Sankt Augustin and covers rural areas as well as the Bonn-Rhein-Sieg University of Applied Sciences. It consists of multiple P2P links with distances ranging between a few hundred meters up to ten kilometers. A visualization of the network is shown in Figure 1.

Figure 1. Rhein-Sieg-Testbed. Visualization generated with Google Earth.

The Rhein-Sieg testbed focuses on a practical build-up instead of relying solely on using radio-towers. The main reasons for this are either the unavailability of radio-towers at the desired locations or the enormous cost factor of renting or building up such tower.

To build a WiLD node, we use Single-Board Computers (SBCs) with multiple (mini-)PCI-e slots holding the WiFi transmitter. We use three different types of WiFi cards[2] all based on the same chipset and using the same Linux open-source driver (ath9k). The SBCs are placed in outdoor suitable enclosures mounted at the desired places. As a power source, we use either an available grid connection or, when a grid is unavailable, a solar system. The WiFi cards are connected with coaxial cables to the antennas. In general, we keep the cables as short as possible to minimize the additional attenuation. In our testbed we use two different types of cross-polarized antennas with 19 and 25 dBi gain[3].

C. Signal Flow measurement with WiFi cards

We use COTS hardware instead of industrial-grade signal generators and spectrum analyzers. To validate propagation models for WiLD, RSS measurements are needed. In [19] we compared different methods of measuring the RSS using IEEE802.11 COTS transmitter. We found that for specific models of WiFi cards the accuracy of the RSS is sufficient for propagation model validations. In this work, we use the

[2]We use explicitly the following models: Ubiquity SR71e, Mikrotik R11e-5hnd and Mikrotik R52hn.

[3]We use antennas from the vendor Mars with the model names: MA-WA56-DP19 and MA-WA56-DP25.

described RSS value reported by the drivers in the so-called radio-tap header. The transmission power of the WiFi cards can be set fixed to a certain amount.

D. Link Budget estimations

In [2], the authors conduct a basic link-budget calculation for WiLD links using the following equation:

$$P_{RX} = P_{TX} - L_{C_{TX}} + G_{TX} - L_P + G_{RX} - L_{C_{RX}}$$

This equation describes the signal flow from the transmitter to the receiver summarizing the various equipment. P_{RX} and P_{TX} are the received and transmitted power at the WiFi card in dBm. We summarize the additional loss due to cables and connectors at the receiver and transmitter with the parameters $L_{C_{RX}}$ and $L_{C_{TX}}$. The antenna gain is described by the parameters G_{RX} and G_{TX}. Finally, L_P is the signal attenuation due to the propagation. However, this estimation is prone to errors for various reasons. An obvious reason is that all the COTS hardware is manufactured with certain tolerances. In addition, the maximum antenna gain is only reached when the antennas on a link are perfectly aligned. Due to these systematic errors, a certain deviation between the measured and estimated path loss is expected. Based on the link budget calculation, it seems to be possible to derive a *first estimation* for the absolute error based on the propagation of errors of the different components. We assume for $G_{RX|TX}$ an error of ± 2 dBi, for $L_{C_{RX|TX}}$ an error of ± 0.5 dB. For $P_{RX|TX}$ we used our results obtained in [19] and assume an error of ± 1 dBm. Using the root of square sum, we therefore estimate an error for the path loss of ± 3.2 dB.

V. Experiments and Results

This section provides the descriptions and results of several experiments in the context of propagation for outdoor wireless links.

A. Ground-Reflection with omni-directional antennas

As described in Section III-B, the Two-Ray model is a widely used approach to model outdoor radio-propagation. Our first experiment aims at answering the following question: Is ground-reflection a measurable phenomenon for IEEE802.11 outdoor links? We therefore conducted the following experiment. At a rural area close to Bonn, we chose a long street with the following attributes: free of interference from other participants on the 5 GHz band and flat and regular-shaped terrain. We mounted two wireless nodes on poles at three meters and attached an omni-directional antenna on each side. One pole had been fixed at a certain location, the other pole was mounted using a custom-made structure on top of a car (cf. left picture in Figure 3). To measure the distance, we used a measuring wheel attached to the structure of the car (cf. left picture in Figure 3). We also experimented with a GPS-based distance estimation system but found it (and its accuracy) hard to handle. On the ground-mounted pole, we generated constant traffic and measured the signal strength at the car at different distances. The result of this experiment are shown in Figure 3.

The abscissa in Figure 4 implies a logarithmic scale and shows the distance between the car and fixed-pole between 20 m and 300 m. We plotted our measurements of P_{RX} (black), our estimation of the two-ray model(red) and the FSPL (blue). We implemented the required calculations for the Two-Ray model based on the descriptions available in [17] in Mathworks Matlab. A limitation for our measurements is the minimum signal level required for the card to report the values shown as $RXLevel_{min}$ in Figure 4.

We found that the measured received power followed the estimated maximum and minimum of the Two-Ray model. This result clearly indicates that ground-reflection is a measurable phenomenon for IEEE802.11 outdoor links using omni-directional antennas.

B. Testbed with directional antennas

In this section, different propagation modeling approaches for long-distance IEEE802.11 links are evaluated using the results provided by SPLAT! in comparison with measurement from our Rhein-Sieg testbed (cf. section IV-B). This experiment aims at answering the following question: Is it possible to predict the path loss in a real-world WiLD with well-known propagation models?

The results of the experiment are shown in Figure 2. The figure shows on the left ordinate the measured and estimated path loss in dBm using the bar plot and on the right ordinate the link distance. On the abscissa, we plotted the name of the link from our testbed (cf. Figure 1). Note that every link is added twice with an inverted role of transmitter and receiver.

We obtained the path loss for the different links in our testbed using the methodology described in Section IV-D. There are various aspects regarding the results presented in Figure 2 that need additional discussion.

Except for the two shortest links, the Longley-Rice model and the FSPL equation estimate similar path loss values. This indicates that according to the used data no terrain indicated obstructions were present that could have caused diffraction attenuation. This was expected and correlates with our conducted sight surveys. In addition to that, no ground-reflection effects are incorporated by the Longley-Rice model for most of our links.

The path loss was only predictable (within our estimated error range of $3.2dB$) for 6 of our 14 evaluated links (B-A, D-C, G-H, H-G, I-H, H-I). A notable fact is the estimation accuracy using either FSPL or Longley-Rice especially for the two pairs of the longest links. We assume practical reasons for this effect.

The antennas at the locations G, H and I (which correspond to the predictable links) are mounted on exposed positions. For example, at location H we used a 96 m high radio tower and the antennas at location G were mounted on a 20 m high building located on a hill. From our conducted site surveys, we conclude that these locations provide clear conditions for a LoS propagation.

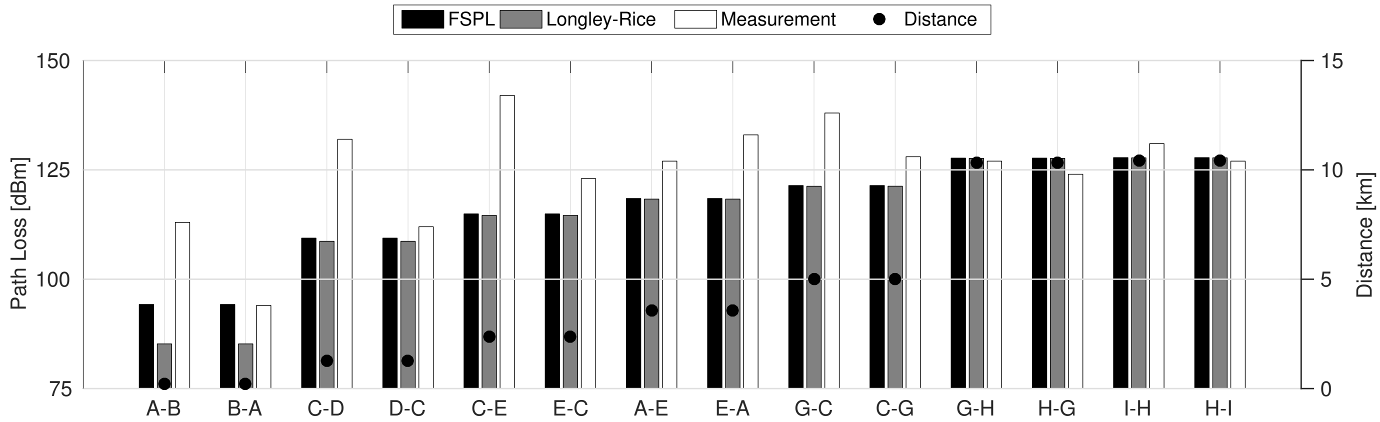

Figure 2. Experiment 2: Path loss for 7 different links in our long-distance testbed.

Figure 3. Experiment 1: Measurement Setup for two-ray path loss verification. Omni-directional antennas mounted on the bottom of the outdoor-enclosures.

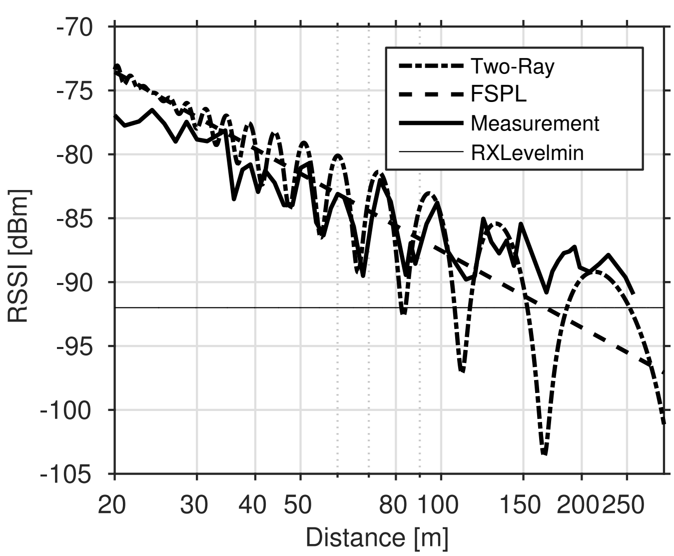

Figure 4. Experiment 1. Two-Ray Path Loss Model with omni-directional antennas. Parameter of Two-Ray model: Frequency: 5180. Polarization: Horizontal. Ground conductivity (δ): 0.125 S/m. Ground relative permittivity (ϵ_r): 5

For the other locations or links, we found different circumstances that can lead to additional attenuation. It is not possible for a radio propagation modeling software such as SPLAT! to account for these circumstances. At the moment, we are unable to precisely quantify these additional attenuations, but we want to provide first ideas in the following. For the links G-C and C-G, we found a line of trees significantly ranging in the first Fresnel zone. SPLAT! does not account for vegetative cover.

At location C, we attached all antennas with a self-made mounting to a chimney as shown in Figure 5. We assume several issues with this construction. The right antenna in Figure 5 is used for the links C-D and D-C. We assume that we mounted the antenna too close to the chimney, leading to unwanted effects in the near-field of the radiation pattern. The antenna on the left side in Figure 5 is possibly prone to reflection or diffraction from the roof or ridge. It is impossible for radio propagation models to automatically account for these installation related issues.

The antennas at location A are mounted inside an electricity pylon made out of metal. One possibility for the additional path loss on the links including location A may be this surrounding metal construction.

Besides the additional path loss for the majority of our testbed links, we found another interesting phenomenon. For certain links, for example C-E and E-C or A-B and B-A, the path loss was asymmetric when changing the role of transmitter and receiver. If this asymmetric path loss can be correlated with the circumstances described in the last paragraphs, this

Figure 5. Build up at location C.

leads to interesting but open research questions.

C. Influence of environmental factors

Our third experiment aims at answering the following question: Is there a measurable influence of environmental factors to the propagation attenuation on long-distance links? We concentrate on three different factors: the temperature ($^{\circ}C$), the humidity ($\%$) and the atmospheric pressure (hPa). All values are measured using a weather station mounted at point G of our testbed (cf. Figure 1). We measured the Received Signal Strength Indication (RSSI) of two different links (H-G and C-G in figure 1) on 275 days 2015 with a granularity of 1 minute for the RSSI and 15 minutes for the environmental factors.

Overall, no statistically significant influence of the environmental factors using the overall dataset can be obtained. This confirms the results found by [12] but stands in marked contrast to the results obtained in [13].

VI. Conclusion and future work

In this work, we presented the results obtained during our experiments with propagation of outdoor WiFi links. We described different models and an open-source software we used for our tests. We found that for short outdoor links with omni-directional antennas ground-reflection is a real-world phenomenon leading to destructive and constructive interference at the receiver. We therefore conclude that the Two-Ray Path Loss model is superior when estimating these links.

For long-distance links with directional antennas, we found the FSPL or the Longley-Rice model show similar results in our testbed. We also described how both models are only accurate for links where antennas are mounted on exposed locations. For the majority of our links, we described that a path loss estimation does not hold. The measured path losses exceed the estimated values significantly. We currently assume, that different circumstances from our build-up lead to these additional attenuations. We conclude that for practical WiLD a good site survey is essential. Solely focusing on propagation estimation with path loss models does not account for real-world circumstances. Finally, we analyzed different environmental factors. In our testbed, we could not obtain a statistical significant correlation between temperature, humidity or atmospheric pressure and the RSS.

A. Future work

Several possible follow-up items arise from our results. We aim to investigate further the additional path loss we obtained for several of our links. Another interesting topic is the environmental factors. Our goal is to set up a link more isolated from RSS influencing factors such as interferences from other participants.

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