Wireless in The Woods: Experimental Evaluation of IEEE 802.11a/b/g in Forested Environments

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***Abstract*—We study the feasibility of using IEEE 802.11a/b/g in forested environments. Our particular interest is to identify potential wireless communication technologies for spanning a ground network in the woods to study the foraging and hunting behavior of bats in the wild. We are working on ultra-low power communication devices to monitor contact times and to localize bats in their natural habitat. For collecting and aggregating the received information, a stationary ground network is planned but little is known about the signal attenuation due to shadowing and fading and the resulting packet error rates in such environments. Thus, we experimentally studied selected wireless LAN technologies in an extensive set of measurements. We report our findings that also help selecting protocols and configurations in other sensor networking applications.**

I. Introduction

The use of Wireless Sensor Networks (WSNs) has become more ubiquitous in the last years [1]. Under the umbrella of Cyber Physical Systems (CPSs), many research activities are going on investigating topology management, wireless access, routing and data aggregation, security, and many others [2]. Still, many of the early findings in this domain have rarely been applied in practical applications. In the scope of the BATS research group, we explore the feasibility of using sensor networking technology for tracking bats in their natural habitats.[1] State of the art technology for such observations is still radio telemetry [3]. This, however, is extremely labor expensive and allows to track single individuals with limited localization accuracy. In order to study the animals' behavior, contacts and precise tracking would be beneficial.

To this end, we plan a stationary sensor network deployed in a forest environment that collects and aggregates such contact information. In a first step, we explore the feasibility of different wireless communication technologies for this ground network. Given that distributed real-time localization algorithms require a certain (depending on the algorithm even very high) data rate between the nodes, wireless LAN according to IEEE 802.11a/b/g might be a good candidate.

We realized that signal attenuation due to shadowing and fading constitutes a substantial problem in forest environments. To the best of our knowledge, there is no study comparing the performance of IEEE 802.11a, IEEE 802.11b, and IEEE 802.11g in such environments. Thus, we experimentally studied the applicability of the mentioned technologies in an extensive set of measurements. In the following, we report our findings that also help selecting protocols and configurations in other sensor networking applications.

[1]Dynamic Adaptable Applications for Bats Tracking by Embedded Communicating Systems, http://www.for-bats.de/

II. Related Work

In the literature, the performances of the IEEE 802.11a/b/g standards has been discussed in depth for line-of-sight scenarios as well as indoor and urban environments [4]–[6]. Yet, knowledge about the behavior in the countryside and wilderness is not fully understood, especially for forested surroundings.

Research on the impact of vegetation on wireless communication has been focused mainly on general radio wave propagation and attenuation models, which have been either developed from empirical data [7]–[11] or have been derived analytically [12].

Some studies have been focusing on the communication through the canopy where one station is situated at a prominent height over the coverage area [7], [13]. However, placing the communicating nodes in or above the canopy would make deployment and maintenance of our sensor network more difficult, and, as bats are flying blow the canopy to hunt for prey on the ground, this would influence communication negatively. Hence, the decision was taken to place the nodes near the ground.

Most models depend on the type of trees and on the used frequency, even though only few studies have been conducted in the ISM band. Therefore, most models are not applicable to the IEEE 802.11a/b/g standards as they do not cover the used frequencies of 2.4 GHz and 5.8 GHz, respectively [10], [11], [14]–[16]. A model, that also covers the ISM band, is proposed in [17]. The model is valid for frequencies of 1 GHz to 60 GHz and is very accurate as it combines edge diffraction, ground reflection and the signal going through vegetation. As it takes into consideration the occurring tree species, tree height, tree spacing and leaf dimension it can be applied only to a well-structured and precisely describable environment, which is not given in a naturally grown forest. Therefore, the model is not applicable if the performance in more general scenarios is of interest. The performance of the 2.4 GHz band in comparison to the 5.8 GHz band is evaluated in [8], but only in two forest types, an oak tree forest and an eucalyptus woodland.

The impact of pine trees on the communication using IEEE 802.15.4 has been studied in [18]. In a similar way, the throughput and received signal strength of IEEE 802.11b/g have been evaluated in a wooded area in [9]. However, to the best of the authors' knowledge, there is no study comparing

(a) Light forest (b) Dense forest (c) Light forest with thick undergrowth

Figure 1: Pictures of the three environments

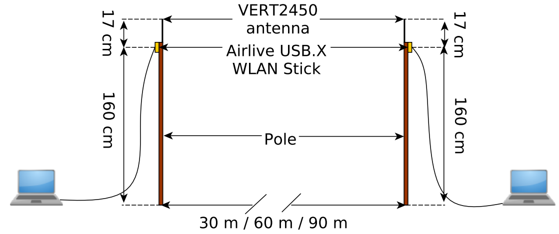
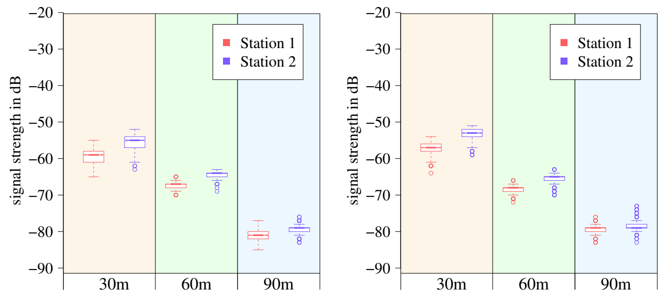


Figure 2: Measurement setup. We used two poles to mount the antennas at a height of 1.6 m in a distance of 30 m, 60 m, and 90 m



(a) Bit rate of 1 Mbit s^{-1} (b) Bit rate of 11 Mbit s^{-1}

Figure 3: Results for IEEE 802.11b and the dense forest scenario

the performance of IEEE 802.11a, IEEE 802.11b, and IEEE 802.11g in various different forest environments.

III. Measurement Environment

Three different forested environments were chosen for the measurement campaign: a light forest (cf. Figure 1a), a dense forest (cf. Figure 1b), and a light forest with thick undergrowth of about 2 meters height (cf. Figure 1c). As a reference, free space measurements were performed on a grassland.

The light forest and the undergrowth environments consist of conifers with an average height of 20 meters, a diameter of up to 50 centimeters and no branches for the lower four meters. In the dense forest, the large conifers were accompanied by smaller trees. The light forest was free of ground vegetation, opposite to the other forests.

The most appropriate environment in the scope of the BATS research group is the light forest, as the lack of ground vegetation is preferred by the bats according to [19]. The other forests were included into the measurement campaign to complete the picture.

In the light forest environment three different scenarios were taken into account: line of sight, a few trees between the two stations, and as many trees as possible between the two stations. In the undergrowth and dense forest environments neither line of sight nor a few trees between the stations was achievable.

Overall, we took measurements in six different scenarios, in the remaining part referred to as free space, line of sight, few trees, many trees, dense forest, and light forest with undergrowth.

IV. Measurement Setup

The measurements were performed using two measurement stations, both serving as transmitter and receiver (in the following called Station 1 and Station 2, respectively). We used laptop computers (Ubuntu Linux 12.04) connected via USB to a WLAN stick (Airlive X.USB dual band IEEE 802.11a/b/g/n USB WLAN stick with Atheros chipset,[2]) and an omnidirectional antenna (VERT2450 dual band 2.4-2.5 GHz and 4.9-5.9 GHz with 3 dBi gain[3]) attached to the top of a pole (cf. Figure 2) to reduce ground level influences.

[2]Airlive X.USB, http://www.airlive.com/product/X.USB

[3]Ettus Research VERT2450 Antenna, https://www.ettus.com/product/details/VERT2450

One measurement station was placed on a fixed position, whereas the other was moved according to the distance to measure (30 m, 60 m, and 90 m). We used two different modulations for each technology, one for the slowest supported bit rate and one for a higher bit rate. The same frequency was used for both modulations. Table I summarizes all the used configurations.

Therefore, in total six measurements per distance and scenario were performed. For each measurement run, both stations alternated sending 900 packets of 256 B containing a sequence number with a transmission power of 20 dBm. The receiving station logged the received signal strength and the sequence number.

V. Evaluation of the Results

In the following, we discuss the measurement results with the aim to identify best suited technologies for the different scenarios.

A. Impact of Distance

The first and obvious observation is the fact, that with increased distance the received signal strength decreased and, in some cases, not all packets were received. This effect can be seen in Figure 3, which (as an example) shows the measurement results for IEEE 802.11b in the dense forest. The difference between the received signal strength for both stations is due to the fact, that the forest is not really homogeneous.

Up to 60 m, we did not experience any packet loss (data not shown), but at a distance of 90 m, when sending with a bit rate

Protocol	IEEE 802.11a		IEEE 802.11b		IEEE 802.11g	
Channel	Channel 44		Channel 1		Channel 1	
Frequency	5.220 GHz		2.412 GHz		2.412 GHz	
Modulation	BPSK-½	QAM16-½	DBPSK	CCK	BPSK-½	QAM16-½
Data rate	6 $\text{Mbit}\,\text{s}^{-1}$	24 $\text{Mbit}\,\text{s}^{-1}$	1 $\text{Mbit}\,\text{s}^{-1}$	11 $\text{Mbit}\,\text{s}^{-1}$	6 $\text{Mbit}\,\text{s}^{-1}$	24 $\text{Mbit}\,\text{s}^{-1}$

Table I: Configurations of IEEE 802.11a/b/g used in the measurements

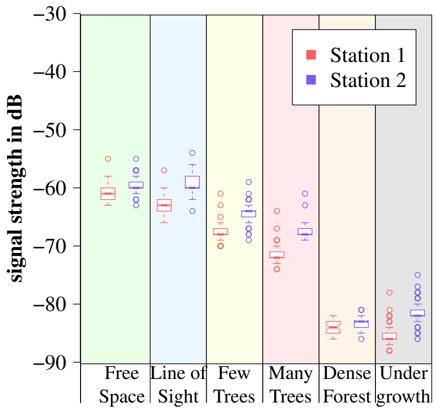
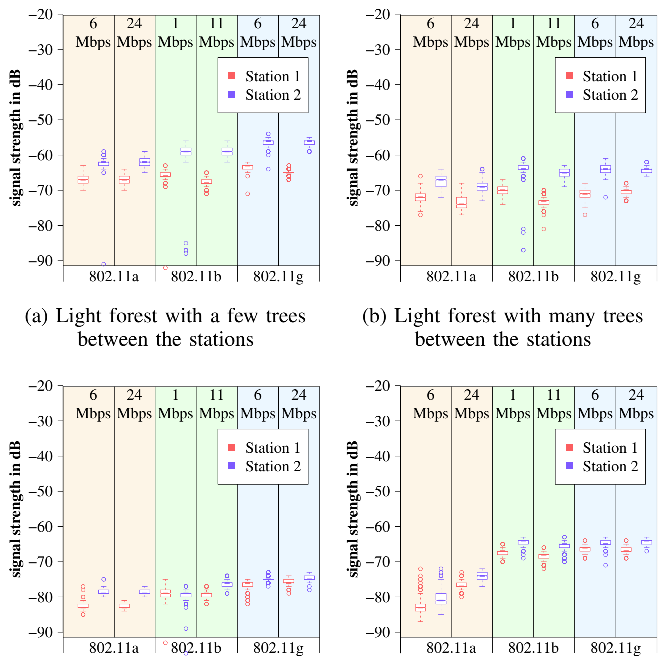


Figure 4: Results for IEEE 802.11a using a bit rate of 6 $\text{Mbit}\,\text{s}^{-1}$ and a distance of 90 m



(a) Light forest with a few trees between the stations

(b) Light forest with many trees between the stations

(c) Light forest with undergrowth

(d) Dense forest

Figure 5: Comparison of the protocol standards in various environments at a distance of 60 m

of 11 $\text{Mbit}\,\text{s}^{-1}$, the receiver is not able to decode 25 % to 55 % of the packets. When the bit rate is throttled down to 1 $\text{Mbit}\,\text{s}^{-1}$, the transmission is very stable and the loss rate is close to 0 %. A similar behavior can be observed for IEEE 802.11a and IEEE 802.11g as well as for the other environments (data not shown). The packet loss ratio for the largest measured distance of 90 m increased to almost 100 % when the forest becomes thicker and more impenetrably.

B. Influence of the Scenario

When comparing all six scenarios, we see a steady decrease in the received signal strength as the environment becomes thicker and more impenetrably. This trend is shown in Figure 4 for IEEE 802.11a, a bit rate of 6 $\text{Mbit}\,\text{s}^{-1}$, and a distance of 90 m.

As we are interested in very sparsely crowded forests, we are primarily interested in the differences compared to the free space (grass land) measurements. We see that the received signal strength slightly differs (this is for the two leftmost scenarios in our figure). Although in both scenarios the measurement stations had a direct line of sight between each other, the received signal strength clearly decreases in the presence of some trees. An explanation for this behavior could be multipath effects, which are even more significant in the light forest scenario.

The same trend of a decreased received signal strength as the environment becomes thicker can be observed also for IEEE 802.11b and IEEE 802.11g as well as for other distances (data not shown).

C. Comparison of the Communication Standards

In order to help taking decisions which wireless LAN standard to choose in which scenario, we finally compare the results according to the different technologies and configurations. Figure 5 gives an overview of the most expressive results regarding the comparison of the standards. Here, we fixed the communication range to 60 m. As can be seen, none of the three standards is definitively outstanding.

In all four graphs a slightly better performance of IEEE 802.11b and IEEE 802.11g can be observed. This is most probably due to the fact that shadowing and fading have a stronger impact with increasing frequency. In the light forest with a few trees between the stations, many trees between the stations, and a thick undergrowth (cf. Figure 5a, Figure 5b, and Figure 5c, respectively), the difference between the two protocol standards sending in the 2.4 GHz band and IEEE 802.11a is negligible. As can be seen, the trend increases as the forest becomes thicker and more impervious. In comparison with the results from the dense forest, the received signal strength of IEEE 802.11a is reduced by 10 dBm to 20 dBm (cf. Figure 5d).

A rather unexpected behavior can be observed when taking into consideration the percentage of received packets. As with increased distance the packet loss becomes a more and more considerable issue, we focus on the largest measured distance of 90 m, shown in Figure 6. For the sparser scenarios, we experienced almost no packet loss (at least 90 % reception rate),

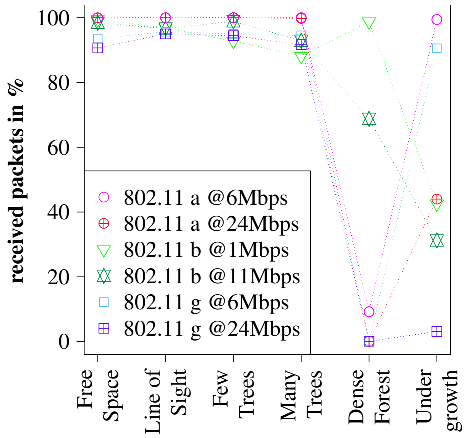


Figure 6: Percentage of received packets at a distance of 90 m

independent of the protocol standard and bit rate. However, this is not the case for the two scenarios dense forest and undergrowth. Comparing the percentage of received packets for IEEE 802.11a with a bit rate of 6 Mbit s^{-1} with the received signal strength shown in Figure 4, we see that the two measures do not coincide. Although the received signal strength of the two scenarios is in the same range, we experience a huge drop in the number of received packets in the dense forest scenario. A similar behavior can be observed for the other protocol standards and bit rates (data not shown).

VI. Conclusion and Further Work

In order to evaluate the performance of the different IEEE 802.11 protocol variants in forested environments, we performed measurement campaigns in three different forests as well as in a grassland scenario. The evaluation of the packet loss rate and the signal strength shows that the performance is influenced by distance as well as the density of the forest. In particular, the environment has an even bigger impact. Slightly moving a node (e.g., one meter to the side) can influence the performance even more than changing the distance between the stations.

It turned out that there is no clear winner when looking at IEEE 802.11a/b/g. Depending on the scenario, the performance of the protocol variants changes substantially. The results clearly show that the upper bound for the distance between the two communicating stations in a forested environment is about 90 m, or, depending on the scenario and standard, even below. In the scope of our BATS project, this finding makes it necessary to deploy a rather dense ground network.

We can also conclude that further investigations have to be performed to get deeper insights about the influence of different kinds of forests on IEEE 802.11a/b/g. This could lead, for example, to some best practices definition for optimally placing nodes in the woods.

VII. Acknowledgments

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