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Experimental Design and Analysis of Transmission Properties in an Indoor Wireless Sensor Network

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Abstract—In this paper, we systematically investigate different factors and their effects on the wireless transmission properties using a full-factorial experimental design of a wireless sensor network in a real-world indoor environment. We quantify the impact of primary factors such as the wireless channel, physical position, transmission power, and their interactions on the received signal strength (RSS). While some of our results support conventional assumptions, this study also shows that there are many properties which are in contrast to existing findings. For example, there is no significant correlation in the measured RSS between different but equally-distant transmitters, yet the correlation coefficient between two transmitters is above 94%. In addition, changing the wireless channel even in a static network scenario results in highly unpredictable interaction with other factors and significantly influences the measured RSS.

Since the analyzed network only consists of low-cost, commodity transmitters, the results of this experimental analysis can serve as valuable insights in planning and deploying wireless sensor networks in different application scenarios.

I. INTRODUCTION

One of the most crucial assumptions in wireless network research is made on the behavior of the wireless channel. Because wireless channel characteristics are in general more environment-dependent than characteristics of wired channels, those assumptions are also the most arguable ones. While many papers assume symmetric wireless links and a predictable received signal strength (RSS), others strongly disagree and characterize wireless signal behavior as highly erratic, uncorrelated, and unpredictable. For example, in the well-known paper “The Mistaken Axioms of Wireless Network Research” [1], Kotz et al. react on the simplifying assumption of the wireless signal behavior and demonstrate that such assumptions are highly unappropriated under real-world conditions. They present a set of experiments using IEEE 802.11 to justify that most of the protocols relying on symmetric links and predictable RSS are contrary to the facts. On the other hand, another well-known paper, “RSSI is Under Appreciated” [2], argues that RSS values are stable over time and that certain symmetric behavior of the signal propagation, especially in case of packet reception rate (PRR), can be observed. Yet, in [3], the authors show that RSSI (RSS Indicator) values are highly variable and that there is less correlation between RSS and packet error rate in outdoor environments. Similarly, there is a number of other papers (such as [4], [5], [6]) that report on different wireless channel behavior for various network settings.

Although results are oftentimes different, the common characteristic among many existing contributions is that the wireless link analysis is not the focus of the paper itself, but it is rather used to empirically support wireless channel assumptions necessary as a precondition for the different design objectives (e.g., such as throughput optimization, error correction, or security-related problems). Hence, in such cases there is a lack of an extensive experimental design and systematic evaluation of the wireless channel.

In contrast, this work is not motivated by justifying an existing protocol relying on specific channel characteristics, but its contribution is focused on a systematical evaluation of the wireless channel common to an indoor, single-hop, wireless sensors networks in which the sensor deployment is centrally controlled by the user. Moreover, the focus of this paper is not only to report that, e.g., the wireless channel is either highly erratic or stable, but to understand how primary factors, such as a physical position, transmission power, link direction, and transmission frequency interact and how much each of these factors contributes to the overall variation of the signal behavior. To achieve this, we conduct long-term measurements following a full-factorial experimental design with repetitions as described in [7].

The remainder of the paper is structured as follows: Section II introduces the testbed and the full-factorial design. We then intensely present the analysis of the experiment’s outcome in Sect. III and discuss the results in Sect. IV which also concludes this paper.

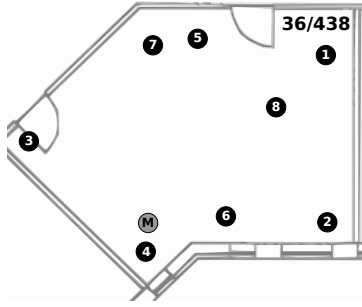
II. TESTBED AND EXPERIMENTAL DESIGN

This section describes the physical testbed and the applied factorial design of the experiments.

A. Testbed Description

The experiments took place in a lecture room, which is laid out for ca. 25 persons representing a realistic indoor environment, and is common to different WSN applications, e.g., temperature monitoring, intrusion detection, or similar indoor environmental control systems. The size of the room allows a placement of nodes in a single broadcast domain in which every node is in line of sight of all other nodes. A total of 8 sensor nodes were placed at the ceiling of the room, each with a distance of ≈ 35 cm to the ceiling’s surface.

Figure 1 presents the sensors placement inside the building. Beside the sensor nodes (referred to as *slaves*), the figure also



Node	1	2	3	4	5	6	7	8
1	0 (l_{11})	-	-	-	-	-	-	-
2	3.5 (l_{12})	0 (l_{22})	-	-	-	-	-	-
3	6.5 (l_{13})	6.8 (l_{23})	0 (l_{33})	-	-	-	-	-
4	6.9 (l_{14})	4.8 (l_{24})	3.7 (l_{34})	0 (l_{44})	-	-	-	-
5	3.3 (l_{15})	4.6 (l_{25})	3.4 (l_{35})	4.9 (l_{45})	0 (l_{55})	-	-	-
6	4.4 (l_{16})	2.5 (l_{26})	4.2 (l_{36})	2.5 (l_{46})	3.3 (l_{56})	0 (l_{66})	-	-
7	3.9 (l_{17})	5.1 (l_{27})	2.8 (l_{37})	4.8 (l_{47})	0.65 (l_{57})	3.4 (l_{67})	0 (l_{77})	-
8	1.7 (l_{18})	3.0 (l_{28})	5.0 (l_{38})	5.3 (l_{48})	1.8 (l_{58})	3.0 (l_{68})	2.4 (l_{78})	0 (l_{88})

Figure 1. Topology showing the placement of the sensor nodes and the distance matrix in meter (names in braces specify link identifiers).

includes a *master* marked with 'M'. The master node plays the role of a sink that coordinates the experiment and collects samples measured by slaves. In addition, the table in Fig. 1 presents all distances between nodes and assigns unique link identifier.

As sensor devices, MICAz motes [8] were used and programmed with TinyOS [9]. The motes are equipped with an 8 MHz Atmel ATmega128L processor, 128 kByte ROM, 4 kByte RAM, and a TI CC2420 transceiver [10] operating on the 2.4 GHz ISM band and providing a maximal transmission rate of 250 kbps. Except the master, all nodes were battery-powered.

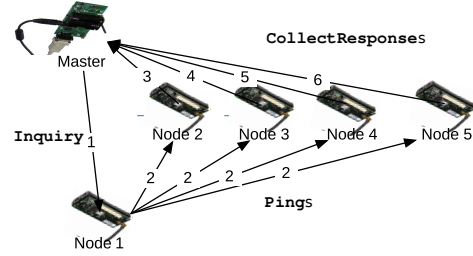


Figure 2. Steps for collecting and gathering of samples.

	rep. 1	rep. 2	rep. 3	rep. 4	rep. 5
start	Mon 14:36	Tue 04:57	Tue 19:18	Wen 9:39	Thu 00:00
end	Mon 23:35	Tue 13:55	Wen 04:16	Wen 18:37	Thu 08:58

Table I
START AND END TIMES OF ALL REPETITIONS.

B. Factorial Design

The objective of our experimental design is the identification and estimation of factors influencing the RSS. Following the terminology of a factorial design, the RSS represents the response variable. We subdivided factors in primary and secondary ones according to a full factorial design [7].

Primary factors (predictor variables) and their possible levels are set as follows:

- 1) Transmission power is the most obvious factor (abbreviated: $TxPower$). The 802.15.4 compliant CC2420 transceiver provides 31 levels, ranging from -25 dBm to 0 dBm [10].
- 2) Channel determines the frequency range that is used for transmission. The CC2420 supports 16 channels inside 2.4 GHz ISM band, each with a bandwidth of 2 MHz [10].
- 3) Under *LinkPath*, we summarize several spatial properties like distance between nodes and node position. The definition of this class of factors is probably the most challenging one, because properties like node positions and length of links are multiple factors, but cannot be changed without influencing each other. We deal with this problem by taking subtopologies as described in Sect. III-B.

We are not interested in the following *secondary factors*, and minimize their influence by fixing their levels or by providing equal conditions for each node:

- 1) The **battery power level** is initially set to maximum on each wireless sensor node. Though we do not evaluate this factor in detail, our impression is that a node

behaves unpredictable (e.g., high packet error rate) when battery capacity is low.

- 2) Several publications report on influences of **objects inside Fresnel zone** [11]. In our setup, all nodes have identical distance to the ceiling (35 cm) and the distance to tables is larger than 1.5 m. Therefore, the first Fresnel zone was never affected by humans, lights or other objects, allowing us to ignore this factor for the rest of the paper.
- 3) Although it is known that **humidity** influences signal strength essentially, we ignore this factor in our indoor environment.
- 4) Inaccuracy during assembly and wear change **node characteristics** that are hard to capture. Due to practicability of the experiment, we have to ignore this factor and assume identical sensor nodes.

C. Collection of Samples

Since experiments were performed in a real-world environment, we used multiple repetitions distributed over several hours to reduce and identify short-term interferences. Also, to be able to capture the impact of human movement, the measurements included busy periods during which the room was used for lectures (more details are given in Section III-C). All together, the evaluation consists of 5 identical repetitions each starting automatically ≈ 5.5 hours after the previous one was finished. Each repetition lasted ≈ 9 hours and consisted of 44 samples per factor level combination

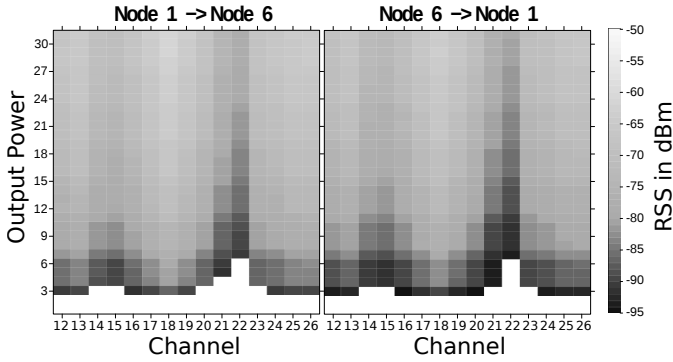


Figure 3. An example of RSS maps in both communication directions.

(see also time table in Tab. I). The principle of the measurements is shown in Fig. 2. Here, the master requests a slave (Inquiry to *Node 1*) to send several broadcasts to all other slaves (Pings to *Nodes 2,3,4,5*). Inquiry includes the desired TxPower and Channel used for Pings. Thereupon, all slaves send the measured RSS of the received Pings in a CollectResponse to the master node. To prevent collisions, CollectResponses are deferred depending on node's id.

III. EVALUATION

A. Effect of Link Direction

Most of the experiments found in literature have shown that link symmetry is rarely given in wireless networks [3], [1], [12]. In the following, we examine link symmetry of our testbed.

To obtain a first impression, Fig. 3 presents two signal maps showing mean RSS values per (Channel, TxPower) tuple for link l_{16} . Although the maps are not identical, they differ only in small deviations. In addition to this first impression, Fig. 4 depicts measured RSS values for both link directions. Again, the figure suggests that the link quality of both directions does not differ much. In addition, Fig. 5 affirms the reciprocity by providing correlation coefficients of all communication links. In this plot, one value shows how the measured RSS of one link direction is correlated to the second direction. Here, TxPower was fixed to a single value, because increasing TxPower leads in general to increasing RSS that would make less-correlated values look as correlated. The coefficients are very close to 1, showing a high correlation of both link directions. However, if we consider correlation among all other links, Fig. 6 shows that no significant correlations can be assumed. So, even if two transmitters are positioned near each other, there is no correlation between their links to a third receiving node.

To quantify the deviation in more detail, we analyze the difference in the RSS per (Channel, TxPower) tuple for each node pair. Formally, for two nodes N_1 and N_2 , this difference is derived as

$$\delta_{c,t}(N_1, N_2) = \text{RSS}_{c,t}(N_1, N_2) - \text{RSS}_{c,t}(N_2, N_1) \quad (1)$$

where $\text{RSS}_{c,t}(N_1, N_2)$ denotes the average RSS computed over 44 samples sent with Channel= c and TxPower= t for

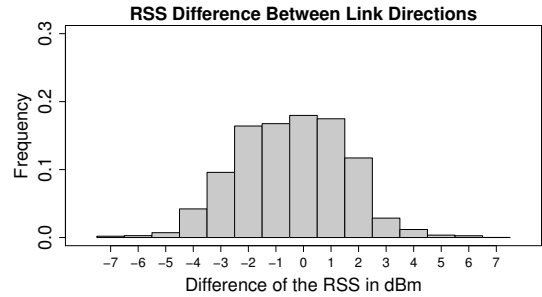


Figure 7. Histogramm of $\delta_{c,t}(N_1, N_2)$. The plot shows the frequency of differences in the measured RSS between both directions of links.

transmissions from N_1 to N_2 . $\delta_{c,t}(N_1, N_2)$ was calculated for all node pairs, all channels, and almost all transmission power levels (low levels with high loss rate were omitted) and is plotted in Fig. 7 in the form of a histogram.

The figure confirms the first impression of the similar looking signal maps of Fig. 3, because the depicted difference is in more than $\approx 92\%$ of all cases smaller or equal 3 dBm. This also indicates that deep fades appear most times on the same channels when evaluating both link directions, since otherwise the difference had to be significant higher. This can for instance be seen when comparing channel 22 with channel 24 in Fig. 3. Here, the difference of the RSS at the same transmission power level is 10 dBm and higher. So if deep fades would not appear at the same channels, this high difference would also be observable when comparing both link directions that is done in Fig. 7.

To quantify the influence of link direction in more detail, we calculate the effects of symmetry in our factorial design by performing an Analysis of Variance (ANOVA). Therefore, we use the factors TxPower, Channel, and LinkPath corresponding to our factorial design of Sect. II. The factor LinkDirection is introduced as artificial categorical factor covering the direction of a link.

Figure 8 summarizes the effects caused by the identified factors over all five repetitions by presenting the percentage of variation (as relation of the sum of squares that are usually shown in ANOVA tables). For the sake of clarity, all one- and higher-order interacting factors with a significance less than 1% are omitted and summed up to *remaining*. In the figure, TxPower indicates the most important factor, followed by the artificial LinkPath factor. LinkDirection, the factor of interest, has compared to other factors no significant effect (about 0.2%). This proves our assumption that link direction has comparatively no relevant influence in our indoor environment.

B. Effect of Node Position

This section investigates in more detail the influence of the position of nodes to the RSS. The objective is to estimate if the distance between nodes is the main reason for the behavior of the wireless channel and in which degree the effect on the behavior is caused by additional spatial characteristics.

In a first step, we consider node pairs with identical distances to a reference node only and compute the effects

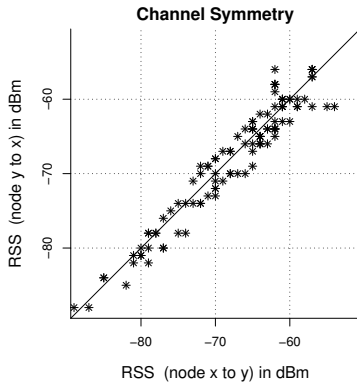


Figure 4. Comparison of the measured RSS of both communication directions of a link.

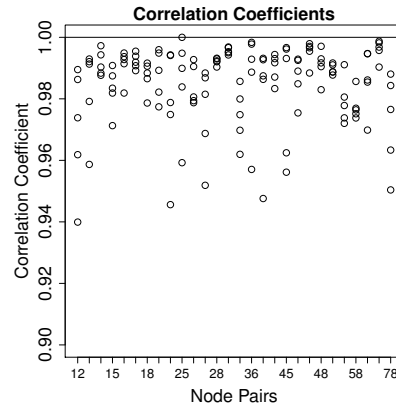


Figure 5. Correlation coefficients of both directions of each link indicate a strong channel reciprocity.

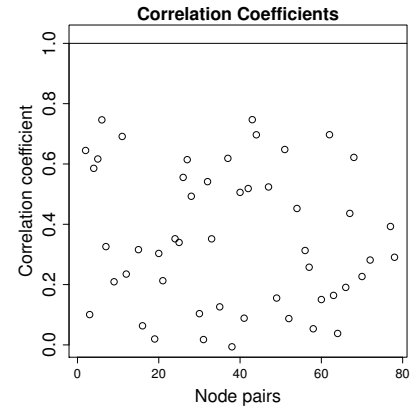


Figure 6. Correlation coefficients between arbitrary links do not indicate significant correlation.

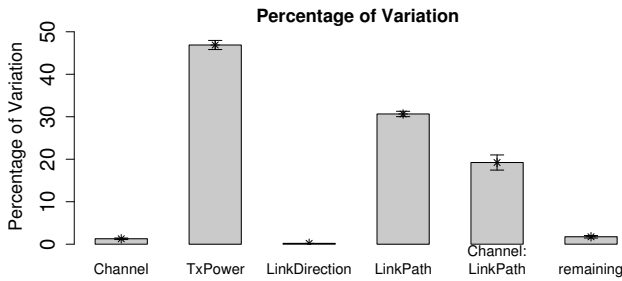


Figure 8. Relative comparison of effects according to the factorial design under consideration of all factors.

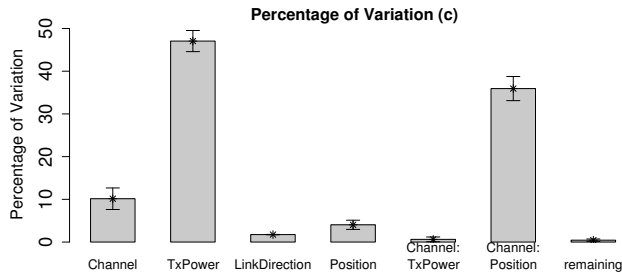


Figure 9. Relative comparison of links 2↔8 and 6↔8 having identical lengths. All effects regarding position are caused by the spatial environment.

according to the factorial design. Referring to Fig. 1, there are three node pairs with identical distances to a reference node. *Nodes 2 and 6 to Node 8* with a distance of 3.00 m, *Nodes 2 and 7 to Node 4* with 4.80 m, and *Nodes 2 and 4 to Node 6* with 2.50 m. Because distances are identical, effects of the `LinkPath` factor or only caused by the spatial characteristics of the outer field of the nodes. Therefore, this factor is renamed in `Position`.

Figure 9 shows the results of an ANOVA regarding links l_{28} and l_{68} . The effects are computed again over 5 repetitions with 95% confidence intervals and effects with a significance less than 1% are omitted. The figure shows that `Position` has an influence of 5% which is clearly less than the influence of `LinkPath` in Fig. 8. But also with identical length of links, the first-order interaction `Channel:Position` has a very

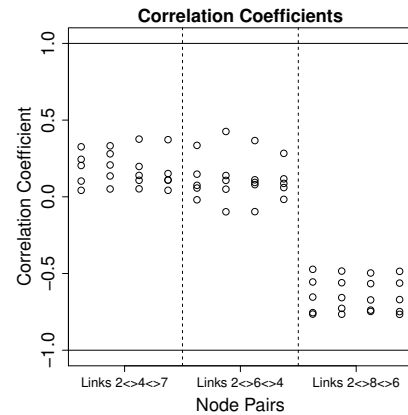


Figure 10. Correlation coefficients of links between nodes with identical distances.

high effect on the RSS response variable (almost 40%). This claims that the exact position of the nodes is not negligible although the links between them have identical length. In our opinion, the high influence of the first-order interaction `Channel:Position` also indicates a hard to estimate or even unpredictable behavior of the wireless channel, because the dependencies between `Channel` and `Position` are hard to comprehend.

While ANOVA already presents the effect of node position, Fig. 10 answers the question if the RSS of two links with identical length but different endpoints are correlated with each other. We fix `PowerTx` again to a constant value to remove the natural correlation that comes with increasing transmission power. The figure shows that correlation of different links is not given, although the links have identical length. All correlation coefficients are far away from an ideal correlation of 1.0. Their scattering over the complete range reveals in addition that correlation of links with identical length is unpredictable in an indoor environment, in which multi-path propagation, signal reflection, and signal diffraction is usual and leads to a signal propagation that is hardly reproducible.

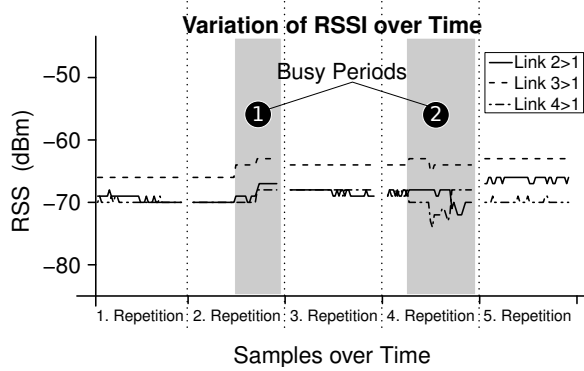


Figure 11. Time-based variation of RSS for 3 selected links.

C. Variation over Time

This section quantifies the variation of the response variable caused by time-based change of the environment by looking at all 5 repetitions. As mentioned in Sect. II, one repetition consists of 44 samples per factor level combination with a duration of 9 hours. In the following, we concentrate on one factor level combination ($TxPower=25$, $Channel=17$) and investigate links l_{12} , l_{13} , and l_{14} (always in *Node 1*'s direction) spanning the lecture room completely.

The trend of RSS is shown in Fig. 11. The highest variation over all 5 repetitions is observed on links l_{12} and l_{14} , on which the RSS varies with 6 dBm between -72 dBm and -66 dBm, and -74 dBm and -68 dBm respectively. Thus, although the RSS is not constant, time over a duration of almost 4 days has less influence to the RSS compared to other factors like *Channel*.

In the figure, two busy periods are marked representing time intervals with a high human activity in the lecture room. At the beginning of the first busy period, the desks were rearranged preliminary to a meeting. This resulted in a minor, yet permanent change in the measured RSS values due to a different multipath signal behavior. During the second busy period, the lecture room was used for a meeting of ca. 12 persons. The meeting took almost the whole fourth repetition and resulted in a higher variation of the RSS values. Especially, the link l_{14} , which is also the longest link in our experimental testbed crossing the entire lecture room shows an increased variation of 6 dBm that is also the maximal variation over all 5 repetitions. Yet, we should mention that the transmission was never impacted in a way that the connection could be lost or significantly effected.

Nevertheless, we recommend not to ignore time-based variation, although its effect is less than the variation that comes with other factors, e.g., *Channel* and its interaction that causes variations of 10 dBm and more (see also Fig. 3).

IV. LESSONS LEARNED AND CONCLUSION

The goal of this work was not to find a general set of wireless channel assumptions applicable to every wireless network, but rather to systematically investigate the wireless channel common to a certain type of WSN applications. In this case, the application scenario consists of an indoor

environment, homogeneous hardware, short distances between the transmitters, and a single-hop wireless network in which all nodes are also in line of sight of each other.

In the following, we summarize our key findings and derive statements supported by the results of the experimental analysis. Although we assume the measured data to be specific to an indoor environment and different results may be obtained under other conditions, e.g., when performing the experiment outdoor, we feel confident that following results are beneficial and hold under similar environmental conditions:

- The RSS measured at the both directions of a link is a highly correlated random variable. This means that signal measurements at one transmitter can be used to make certain assumptions on the signal behavior at the other end of the wireless link. Particularly, the difference between RSS measured at both ends of a link is in 92% of all cases less or equal than 3 dBm.
- Changing the frequency of the wireless transmissions results in a highly unpredictable interaction with other primary factors and can contribute to significant changes on the measured RSS. This means that protocols relying on techniques such as frequency hopping must take strong deviations of the signal strength into account.
- Transmission power has only an isolated, linear effect on the measured RSS. There are no significant interactions with any other primary factor. This means that by increasing the transmission power, the signal behavior does not change but rather it increases proportionally.
- When looking at short-range scenarios, the distance between transmitters cannot be used as an evidence to make any assumption on signal behavior among spatially-separated transmitters (even if transmitters are equally-distant), thereby decreasing the importance of accurate location-awareness.
- Changes in the physical environment impact the wireless link, yet, the link remains relatively stable over time. The 6 dBm variation observed during the experiment's time is not negligible, but small compared to the effects caused by other factors.

To summarize, this work applied a full-factorial experimental design with repetitions to quantify the impact of different factors and their interactions on the wireless signal behavior. Based on a 4-day monitoring and sampling of a real-world indoor WSN, the resulting insights can help in planning and deploying of similar WSNs applications. Finally, the lessons learned from this analysis should assist in designing different network protocols which take advantage of and rely on the properties of the wireless communication.

V. ACKNOWLEDGMENT

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