A Long-Term Study of Correlations between Meteorological Conditions and 802.15.4 Link Performance

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***Abstract*—Outdoor wireless sensor networks are all exposed to a constantly changing environment that influences the performance of the network. In this paper, we study how variations in meteorological conditions influence IEEE 802.15.4 links. We show that the performance varies over both long and short periods of time, and correlate these variations to changes in meteorological conditions.**

The case study is based on six months of data from a sensor network deployed next to a meteorological research station running a continuous experiment, collecting both high-quality link and meteorological measurements. We present observations from the deployment, highlighting variations in packet reception ratio and signal strength. Furthermore, we show how the variations correlate with four selected meteorological factors, temperature, absolute humidity, precipitation and sunlight.

Our results show that packet reception ratio and signal strength correlate the most with temperature and the correlation with other factors are less pronounced. We also identify a diurnal cycle as well as a seasonal variation in the packet reception ratio aggregated over all links. We discuss the implication of the findings and how they can be used when designing wireless sensor networks.

I. Introduction

Changes in the environment can heavily affect the performance of wireless sensor networks (WSNs) that are deployed outdoors. In particular, variations in weather, such as changes in temperature or precipitation, have been reported to impact radio communication, leading to packet loss [1], [2] and affecting link quality metrics [3], [4]. Understanding the effects of meteorological conditions on sensor network communication will help to take such performance issues into account during design and deployment.

Earlier work has analyzed the effects of some meteorological parameters on radio links in sensor networks. However, despite the large body of work on the subject, no community-wide consensus has been reached, and a number of studies arrive at incompatible conclusions. For example, Anastasi et al. report that rain coincides with a decrease in packet reception [1]. Boano et al. find that it does not have a significant impact on network performance [3]. Thelen et al. report improved link quality during times of rain [5]. We believe that such discrepancies are largely due to differences in methodology. Whereas some work considers measurements from on-board sensors, others rely on very coarse data provided by public weather services. Similarly, the duration of observation differs from a few hours to up to a few days.

We address these shortcomings by conducting a six months experiment of a 802.15.4-based sensor network that is collocated with a meteorological research station. The station provides high-quality weather data that is accurate in terms of sensing, time and location. We correlate this data with continuous measurements on the network's communication performance. The experimental design allows us to study the effects of seasonal weather changes in addition to the short-term effects.

Our results characterize distinct short-term and long-term performance cycles that correspond to a diurnal pattern and some seasonal effects. We assess the underlying causes of these variations by showing how the received signal strength (RSSI) and packet reception ratio (PRR) correlate with meteorological conditions. We find that temperature has the strongest correlation with both RSSI and PRR among the studied factors. We observe significant drops in PRR even on strong links with an average PRR above 90%.

Our findings have implications for the design of outdoor sensor networks. We highlight the importance of node placement and what variations to expect in PRR. Furthermore, we believe that our results can inform the design of strategies for mitigating weather effects that deteriorate network performance.

In summary, our three key contributions are:

- Based on a long-term measurement, we show that the overall network performance of our outdoor open space sensor network contains a diurnal cycle and a slower moving seasonal change.
- We show correlations between meteorological factors and the 802.15.4 link metrics RSSI and PRR. By decoupling temperature and humidity, we identify that temperature is the dominating factor. In contrast to previous work, we conclude that rain has no observable impact on either RSSI or PRR.
- Through a systematic analysis over different types of links we show that packet reception consistently maintains a negative correlation with temperature, with links at the edge of reception range showing a stronger correlation.

The rest of this paper is structured as follows. Section II describes related work on link measurements in outdoor sensor networks. Section III details our experimental setup. We describe the most important observations made over the six months period in Section IV and provide an analysis of the correlations between link measurements and meteorological factors in Section V. In section VI, we discuss the implication of our findings, and then conclude in Section VII.

II. Related work

Variations in 802.15.4 link measurements due to meteorological impact on outdoor wireless sensor networks have been studied by several researchers in the past. The results vary, and conclusions on which meteorological effects influence radio transmissions differ. Here we summarize the findings from the sensor network literature.

A. Temperature

Temperature has been the main focus in past research, but there are discrepancies in the findings. Work by Holland et al. [6] concludes that temperature has no impact on RSSI. Their view is also shared by Anastasi et al. who do not observe a change in packet receptions over different distances during varying environmental conditions [1]. In contrast, Boano et al. [3] and Bannister et al. [4] specifically show how higher temperature can reduce the received signal strength on a sensor node. Boano et al. set up a controlled experiment showing a decrease in RSSI as temperature increases [3]. They reason that changes in temperature affect crystal accuracy that induce frequency shifts, and thermal transceiver noise, that may degrade performance [7]. The same correlation between received signal strength and temperature is also reported by Thelen et al. [5].

B. Air Water Content

The influence of the amount of water content in the air has been hypothesized both to improve and hinder radio communication in WSNs. Thelen et al. [5] conclude that a higher relative humidity improves the received signal strength and attribute the enhancement to a change in the reflection coefficient on top of the plant foliage at their deployment site.

On the other hand, Anastasi et al. [1] and Sun et al. [2] report that rain and fog cause a decrease in packet reception ratios. Similarly, Capsute et al. [8] report a drop in signal strength during rain and snowfall. Interestingly, these findings contradict the fact that radio signals on frequencies below 11 GHz should be unaffected by rain and fog [9].

More recent work by Boano et al. [3] shows that rainfall, fog and snowfall have no severe impact on the received signal strength between two motes during non-extreme conditions. They explain the contradiction to earlier findings by arguing that it is the change in temperature that causes degradation in signal strength during times of rain and fog, rather than the amount of liquid water in the air.

A key observation is that the often discussed metric relative humidity can be misleading since it measures the amount of water vapor the air can hold at a given temperature. Thus, relative humidity is highly dependent on temperature, since changes in temperature also change the relative humidity, even though the amount of water vapor in the air stays the same.

C. Temporal Changes

The influences that the environment has on links has also been shown in the past by studying the temporal patterns describing the link quality.

Sun et al. [2] show how PRR fluctuates over a single link during a few days, suggesting the presence of a periodic pattern, following shifts in daytime and nighttime. Others have also noted that there can be a large variation in the received signal strength and radio link performance during daytime and nighttime [3], [4], [5]. These variations are most prominently explained by the changes in temperature.

D. Our Reflections

Based on previous work we identified two aspects that came to heavily influence our experimental design.

First of all, we argue that the type of weather data that is used for comparison has a major influence on the obtained findings. We note that meteorological measurements are obtained in different ways. They can be taken from the sensor board itself [3], [6], using publicly available weather data [2], [3], [10], or by deploying external sensors [1], [5]. The different ways of obtaining the data causes a large variety in the reliability of the measurements, in terms of location, timeliness and sensor accuracy. This also makes it more difficult to compare different findings.

Secondly, we note that previous work, except for [3], conduct experiments running from a few hours to a few days at most. This limits the possibility of experiencing a larger variety of meteorological conditions and capturing slow moving variations in the environment.

III. Experiment Overview

We designed an experiment where a WSN is deployed long-term collecting link measurements, while the environment is closely monitored during all times. We put up a sensor network at a meteorological research station that is equipped with professional-grade sensors for a variety of parameters. This enables us to study the effects of meteorological conditions on the sensor network's operation using high-quality meteorological data.

A. Sensor Network Deployment

The sensor network is comprised of 16 sensor nodes as shown in Figure 1. It is deployed on an open field with no trees or bushes in the surroundings. The sensors are running on a fixed power supply and do not depend on a battery, ensuring continuous operation over the entire long-term experiment. There are four 1.5 m high poles in total which are aligned along a 80 m straight line at distances of 0, 20, 40 and 80 meters respectively. We attach four nodes to each pole, allowing us to create links over a variety of distances. Two

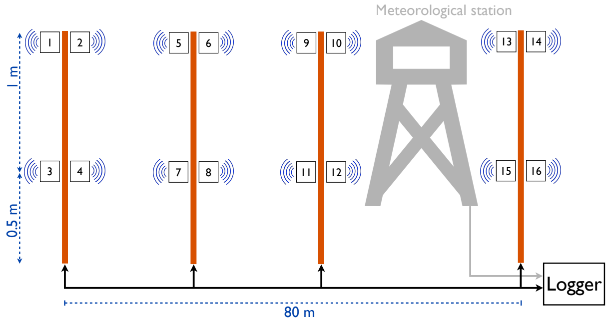


Fig. 1: Setup of the outdoor sensor network. Sensor nodes are labeled 1 – 16. Nodes placed at 1.5m e refer to as high mounted and the ones at 0.5 meters as the low mounted.

nodes are attached to the top of the pole (facing opposite directions), and two nodes are attached to the bottom, 0.5 m above the ground. This allows us to study how different heights and the reflection from the ground influence performance.

We use TelosB nodes [11], which are general purpose sensor nodes that are commonly used in the research community. The sensor nodes are equipped with 802.15.4-compatible CC2420 radio transceivers that operate in the 2.4 GHz ISM band [7]. Their prevalence in research projects and deployments makes them a natural choice for our study. The TelosB sensor node includes sensors to measure temperature, relative humidity and light.

Since the deployment site is at a remote location with very few people having access to it, interference caused by human activity is minimal.

B. Data Traffic Generation

The sensor nodes run a simple program we developed to periodically send packets along each radio link, i.e., to send packets between each possible pair of nodes. The transmission power of the nodes is set to the maximum of 0 dBm. One of the nodes acts as the designated sender, and sends a probing packet, 34 bytes in size, addressed to another node. Packets are sent with an inter-packet delay of 500 ms and each time the sender addresses a different node. If the addressed node receives a probing packet, it immediately sends back a response packet addressed to the sender. At the same time all other nodes overhear the packets being sent and are set to receive and log them accordingly. Every 30 seconds, the role of the sender is rotated among the sensor nodes in a round-robin fashion. This means that we have a total of 240 potential links in our network and the scheme generates at most 15 packet receptions (if all nodes can overhear it) per sent packet. On a typical day the experiment logs about two and a half million packet receptions.

For each received packet, a node logs a local timestamp, source and destination address, sequence number, the signal strength during packet reception, noise floor reading, checksum, payload and the Link Quality Indicator.

We use Sensei-UU, our relocatable wireless sensor network testbed [12], to monitor and control the experiment. All log messages from the sensor nodes are timestamped with a global time and stored for further processing.

C. Meteorological Station

The meteorological station is located near Uppsala, Sweden. The surrounding region is characterized by an average temperature of 16°C during summer and -5°C during winter with an annual precipitation around 450-650 mm. The station is operated by the Department of Earth Sciences at Uppsala University and all the meteorological data from the station can be viewed online [13]. It provides data for the following sensing modalities: temperature (at heights 0.84, 1.95, 4.78 meters), wind (direction and speed at heights 0.8, 1.7, 4.0 meters), precipitation, relative humidity, air pressure, snow depth. It also measures the incoming and outgoing long and short wave radiation that can be used to measure sunlight for example. Each of these values are sampled every ten seconds and an average is computed over ten minute intervals along with the standard deviation. Thus, the station provides measurements with a higher temporal resolution than usually available from public weather services. Since it is collocated with our sensor network, the measurements accurately reflect the meteorological conditions experienced by the network.

IV. Observations

We present findings from six months of data collected between April 1st and September 30th, 2012. The experiment ran continuously during that period and generated approximately 475 million packet receptions. Due to such a large dataset being analyzed, the numbers presented here are based on averages over 10 minute intervals unless otherwise specified. This also matches the meteorological data which is obtained with 10 minute intervals. Figure 2 illustrates the change in mean and standard deviation of RSSI over one link for different time windows. It shows that the first sample stays within one standard deviation for a 10 minute window.

We start by making a number of observations based on the collected data in this section and in the next section analyze and draw conclusions based on correlations between meteorological factors and link measurements.

We first aggregate links to observe general trends over the entire experiment duration. This is followed by looking at one specific link over a shorter time span to highlight more fine-grained observations. In order to limit the scope, we have chosen to present four different meteorological variables based on previous work and our own insights on what is most interesting. They are temperature, absolute humidity, precipitation and sunlight.

A. Overall Packet Reception Ratio

Successful data delivery is an essential performance metric of any sensor network. Figure 3 shows the daily *overall mean PRR*, i.e., averaging all successful packet receptions from all nodes, for each day during the entire six months period. In Figure 3 the PRR changes over the months during the

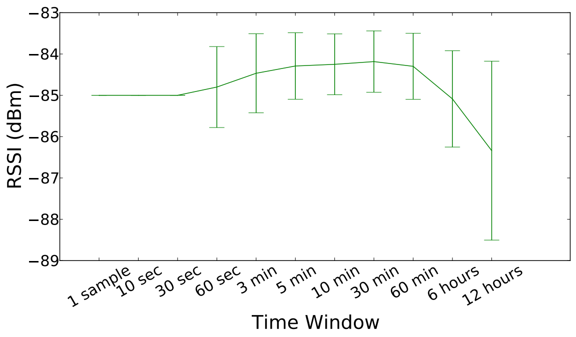


Fig. 2: The RSSI of one link measured over different time windows with mean and standard deviation. The chosen 10 minute time window differs less than 1 dBm in RSSI for one standard deviation.

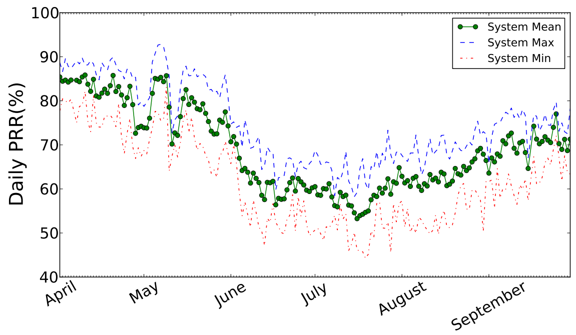


Fig. 3: Daily PRR, computed as an overall average over all links during the entire six months period. Also shown is the minimum and maximum values of overall PRR over 10 minute intervals. There is a clear degradation in PRR during the months June, July and a slow recovery during August.

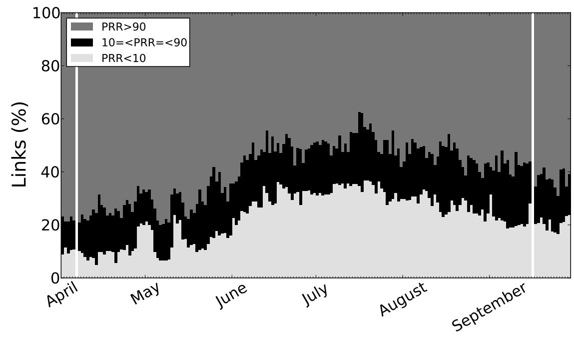


Fig. 4: Percentage of links divided into three categories based on daily PRR average. High quality links decrease in early June and start to recover in August. The white stripes are two days when experiment was not running due to testbed failures.

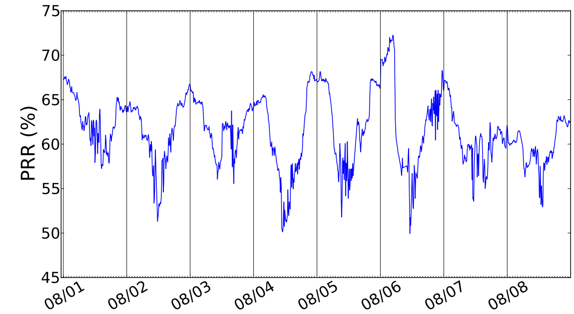


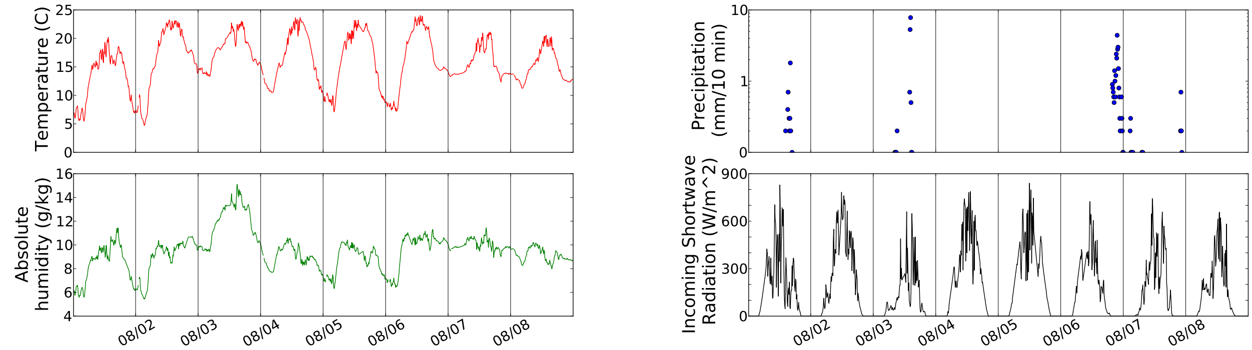
Fig. 5: Overall mean PRR based on all links, computed over 10 minutes, during eight days in August showing a pattern of daytime lows and nighttime highs in PRR. The overall PRR can fluctuate more than 20% during one single day, seen during August 6th. Vertical lines indicate midnight.

experiment. We observe the lowest average overall PRR on July 19th at 44.3% and the highest average PRR on May 7th at 92.8%. It illustrates how the ability of the sensor network to successfully deliver data can vary over long periods. A slow moving change is observed where the overall PRR decreases during the summer months and starts to recover during August.

Next we look at the stability of links and how it changes over time. Previous work such as Srinivasan et al. [14] has shown that PRR exhibits a cut-off behavior where it is typically either very good with a PRR above 90% or very poor with a PRR below 10%, and only a small portion of links have a PRR in between. Based on the same categorization, all the links in our deployment are plotted in Figure 4. First of all we see that the categorization matches with the observed daily PRR, where most links are either very strong (PRR $>$ 90%) or very weak (PRR $<$ 10%). Only about one fifth of the links have an intermediate PRR (90% $\leq$ PRR $\leq$ 10%) throughout the experiment. Note that it is the proportion of strong and weak links that changes throughout the experiment whereas the amount of intermediate links is fairly constant. This can be seen when strong links start to diminish in late May and at the same time the percentage of weaker links increase. This suggests that there are seemingly strong links, with PRR above 90% that can deteriorate over long time periods and become weaker. It implies that a high PRR during deployment is not necessarily a guarantee for a continued high PRR over time.

Figure 4 also shows that the amount of strong links fluctuates between 40-80% during the experiment. Analyzing this further reveals that 30% of all links are identified as being stable throughout the experiment, maintaining a PRR above 90% during all times. This means that about 50% of the links in our network are at some point strong with a daily PRR above 90% but deteriorate and become weaker. The 30% of links that remain stable throughout the experiment are seemingly unaffected by any changes in the environment. These links are categorized by the high-mounted short-distance links in our setup (see Figure 1).

We have illustrated how the network's overall mean PRR changes over the different months of the experiment. Looking at a shorter timescale of a few days illustrates another characteristic of PRR. Figure 5 shows the mean overall PRR, this time computed over 10 minute intervals for eight days in early



(a) Temperature and absolute humidity which is measured as grams of water vapor in kilograms of air.

(b) Precipitation in logarithmic scale and sunlight which is measured as the amount of incoming shortwave radiation in watts per square meter.

Fig. 7: Measurements by the meteorological station during eight days in August. Vertical lines indicate midnight.

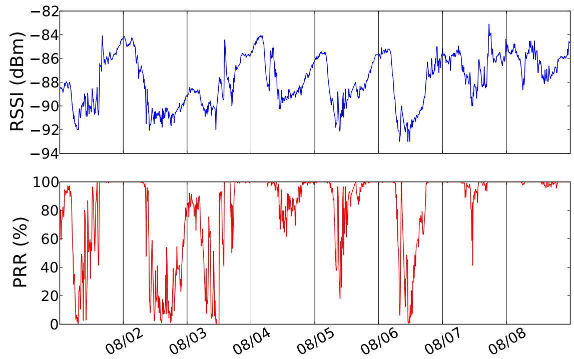


Fig. 6: RSSI and PRR for the representative link during eight days in August. The link appears stable during nighttime but fluctuates during daytime. Vertical lines indicate midnight.

August. Here a diurnal variation in PRR is observed with a trend of daytime lows and nighttime highs. PRR can vary as much as 20% in one day, seen on August 6th.

B. Individual Link Performance

Up until now we have looked at how the aggregation of links in the network perform. The aggregated changes come from changes on individual links. It is therefore useful to look at how single links perform in order to get a more detailed view. To observe changes in individual links we have chosen to study one representative link. We selected the link between the high mounted nodes 1 and 13 that are 80 meters apart (see Figure 1), as our *representative link*. It is at the edge of the communication range while maintaining a high average PRR during large parts of the six months experiment. We argue that in a sensor network deployment, maximizing the distance between nodes while maintaining a high PRR is a desired feature and therefore studying the performance of such a link is interesting. To further highlight observed variations we study the link over a shorter time window of eight days in early August.

To illustrate how an outdoor 802.15.4 link can vary over time, two link measurements of the representative link are presented in Figure 6. It shows the RSSI and PRR measurements over the eight day period. There are observable fluctuations in both parameters with a tendency to decrease during daytime and recover during nighttime.

The link readings in Figure 6 can be correlated with the four selected meteorological measurements in Figure 7. Figure 7a shows the temperature measured by the meteorological station and the computed absolute humidity. Figure 7b shows the measured precipitation over 10 minute intervals, as well as the amount of sunlight, measured as incoming shortwave radiation.

Looking at Figures 6 and 7 suggests that there are correlations between link measurements and meteorological factors. We explore these correlations further in the following section.

V. Analysis

This section details the analysis of obtained measurements with a focus on correlations between the link measurements RSSI and PRR for the representative link and the four selected meteorological factors presented in Section IV.

To measure the correlation, we use Spearman's rank correlation [15] as our metric throughout the analysis. In the same manner as the more commonly known Pearson correlation, it is computed as a score between -1 and $+1$ where 0 indicates no correlation at all. It measures how well two variables *monotonically* increase (or decrease) in relation to one another. It does this by computing the linear dependence of the *ranked* variables as opposed to the variable values themselves. The metric emphasises a correlation where the change in one variable results in a change of the other variable, where the change rate might not be linear but steadily increasing or decreasing.

This section is divided into four parts, namely, temperature, air water content, temporal changes and further analysis. In each part we show correlations to link measurements and

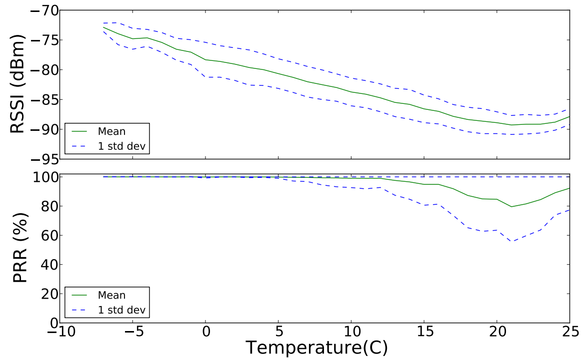


Fig. 8: RSSI and PRR over the representative link and the relationship to temperature measured by the meterological station. Measurements from entire six months experiment. Spearman correlation: RSSI=-0.81, PRR=-0.54

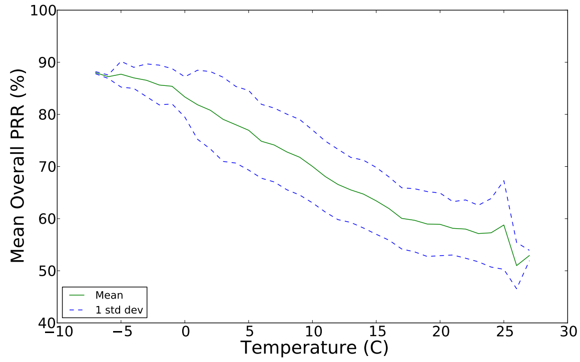


Fig. 9: Relationship between overall mean PRR and temperature for our deployment. Measurements from entire six months experiment.

TABLE I: Summary of the correlations between link metrics and meteorological factors for the representative link.

	RSSI	PRR
Temperature	-0.81	-0.54
Relative Humidity	0.12	0.21
Absolute Humidity	-0.72	-0.44
Precipitation	-0.13	0.06
Sunlight	-0.42	-0.33

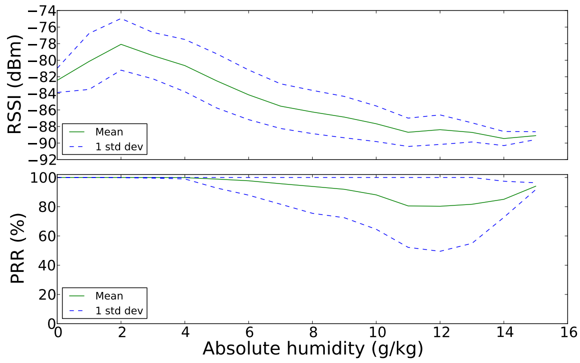


Fig. 10: RSSI and PRR over the representative link and the relationship to absolute humidity in grams of water vapor per kilogram of air. Measurements from entire six months experiment. Spearman correlation: RSSI=-0.72, PRR=-0.44

draw conclusions based on that and discuss how they compare to related work. An overview of the correlations for the representative link can be found in Table I.

A. Temperature

We sort all the link measurements for the representative link into buckets based on the temperature during the measurements. We generate one bucket for each degree of temperature. For each bucket the mean and standard deviation of RSSI and PRR is computed. Figure 8 shows the relationship between temperature and RSSI as well as temperature and PRR. There is a negative relationship between temperature and RSSI, similar to that reported by others [3], meaning that the RSSI decreases as temperature rises. We obtain a strong negative correlation between temperature and RSSI with -0.81 and -0.54 for PRR. For the representative link, when temperature rises above 16 °C the PRR goes below 90% on average. We expect that the increase in both PRR and RSSI around 25 °C in Figure 8 is due to a small dataset at those temperatures.

Now, we look at the overall mean PRR of all links in our deployment, and how it relates to temperature, shown in Figure 9. Again, measurements are sorted into buckets based on the temperature at the time of the reading. It illustrates that as temperature rises more links reach their sensitivity, and thus PRR decreases. The correlation between temperature and PRR can also be observed at this aggregated level, showing that it holds over a long period of time.

Conclusion*:* In accordance with previous work in [3], [4], [5] and opposed to [1], [6] we conclude that there exists a negative correlation between RSSI and temperature. In addition we have shown that there also exists a negative correlation between PRR and temperature in the aggregation of all links of our sensor network, which indicates a systematic degradation of successful packet reception as temperature increases. This was also observed for the representative link, a strong link at the edge of the communication range.

B. Air Water Content

Here we examine how two different measures of water content in the air influence the representative link. We begin with looking at absolute humidity that measures the amount of water vapour in the air. Then, we look at precipitation, in the form of rain as a measure of the amount of liquid water in the air. Relative humidity (Table I) is a is a skewed metric, motivated in Section II-B, therefore we do not study it further.

In the same fashion as before, link measurements are divided into buckets based on the absolute humidity when they

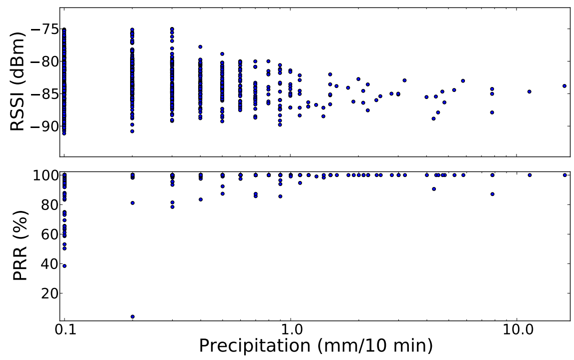


Fig. 11: Scatter plot of RSSI and PRR for the representative link during precipitation. Note the logarithmic scale on the x-axis. Measurements from entire six months experiment. Spearman correlation: RSSI=-0.13, PRR=0.06

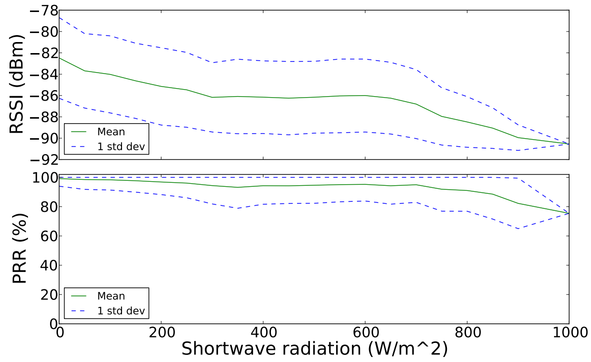


Fig. 12: RSSI and PRR over the representative link and the relationship to sunlight measured by the meteorological station. Measurements from entire six months experiment. Spearman correlation: RSSI=-0.42, PRR=-0.33

were obtained. The relationship between absolute humidity to RSSI and PRR is demonstrated in Figure 10. There is a negative trend in both RSSI and PRR as the absolute humidity increases. The correlation is -0.72 for RSSI and -0.44 for PRR. The positive trend up until 2 grams of water vapor per kilograms of air in Figure 10 is likely due to a small measurement sample at those low levels.

In contrast, precipitation in Figure 11 shows no significant correlation with either RSSI or PRR. Here the correlation factors are -0.13 for RSSI and 0.06 for PRR. Since the precipitation data is sparse the correlations and the plot only include data of when there was precipitation.

Conclusion: There exists a negative correlation between absolute humidity with RSSI and PRR. Our findings regarding RSSI and humidity contradict those of [5]. This is likely explained by the fact that we measure absolute humidity which is not directly dependent on temperature as is the case with relative humidity used in [5]. The implications are that as temperature drops, by definition the relative humidity increases, although the amount of water in the air is the same. This gives rise to a positive correlation between relative humidity and RSSI, also seen in Table I.

However, we know from observing temperature and absolute humidity that they still correlate to a high degree, with a Spearman correlation of 0.75 for the six months experiment. It implies that changes in temperature and absolute humidity occur at the same time to a large extent Therefore it is not clear which correlation factor is most important. This motivated us to investigate further in Section V-D.

Regarding precipitation, in contrast to [1], [2] no correlation between either RSSI or PRR was found. One explanation of the discrepancy could be that they look at precipitation over one or two individual days, and draw conclusions based on that. Despite the fact that we only look at the data during which there is precipitation the correlations remain low and without any clear indication. Our findings on the influence of precipitation on RSSI are however supported by the claims in [3]. One potential source for error is the fact that precipitation is one of the more difficult meteorological measurements to take. However we are confident that the meteorological station provides data with high quality precipitation sensors.

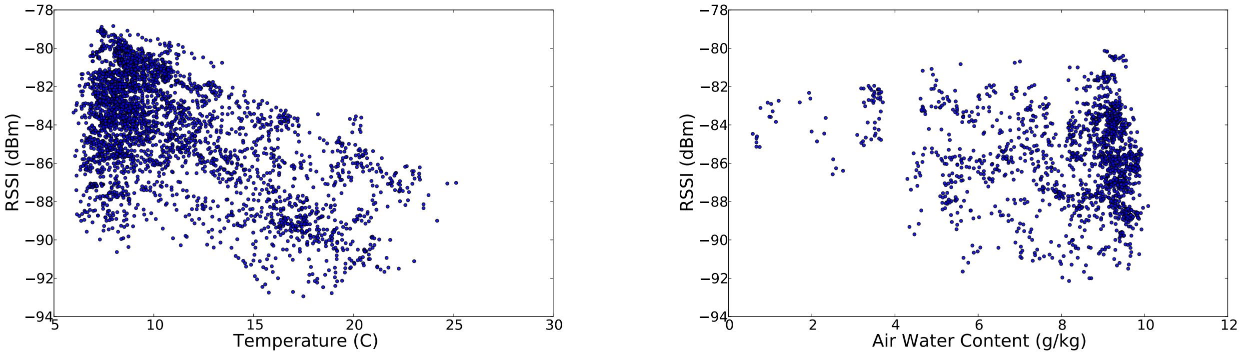
TABLE II: Average PRR and temperature during daytime and nighttime. For the aggregate of all links as well as the representative link.

	All Links PRR	Representative Link PRR	Avg. Temp (C)
Daytime	66.6%	92.8%	13.47
Nighttime	72.7%	98.4%	7.98

C. Temporal Changes

In Figures 5 and 6 we saw a tendency towards nighttime highs and daytime lows in both RSSI and PRR. One way to study the daily variations is to look at the amount of sunlight, measured as shortwave radiation. When the sun is not shining, i.e., during nighttime, the amount of incoming shortwave radiation is 0. We use this metric to look at how different amounts of sunlight influence RSSI and PRR for the representative link, shown in Figure 12. Here again we see a negative trend where more shortwave radiation results in lower RSSI and PRR. The correlation to RSSI is -0.42 and to PRR -0.33, which is lower than the ones for temperature and absolute humidity.

To further analyze the difference between day and night, we sorted all the PRR measurements into a daytime or nighttime category. The daytime category contains all the measurements taken between sunrise and sunset (determined by the shortwave radiation) and the nighttime category contains the measurements between sunset and sunrise. PRR is computed as an average over all links, as well as for the representative link for each of the two categories. The data was from the entire six months and the result is shown in Table II. An overall 6.1% average increase in PRR during nighttime is observed,



(a) RSSI vs. temperature when absolute humidity is fixed to 6 grams of water per kg air. Spearman correlation is -0.43.

(b) RSSI vs. absolute humidity, in grams of water per kilogram of air, when temperature is fixed to 16°C. Spearman correlation is -0.15.

Fig. 13: Scatterplotts of temperature and absolute humidity respectively where the other factor is kept fixed.

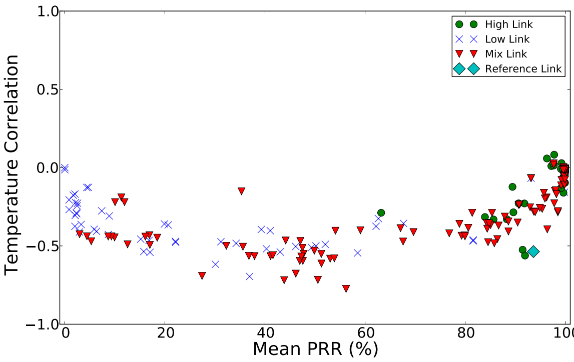


Fig. 14: Correlation between temperature and PRR for all links, computed over the entire experiment. Links are divided into categories high, low and mix based on the height at which the sender and receiver were mounted.

likely caused by the difference in temperature.

Conclusion: We found that PRR is on average higher during nighttime. This can be compared to the ambiguous findings in [2], where they experience both better and worse PRR during nighttime in two different deployments. The circumstances presented in [2] make it difficult to verify the existence of any influence. However, given the correlation between RSSI and PRR on the representative link to shortwave radiation as well as that of temperature (which is typically higher during daytime), we conclude that there is a performance degradation during daytime compared to nighttime. This is also supported by the fact that the average PRR during nighttime was 72.7% whereas only 66.6% during daytime.

D. Further Analysis

Here we detail two different further analysis results that decouple the correlation between temperature and absolute humidity, and show what the correlation between temperature and PRR looks like for all links.

Temperature vs. Humidity: From the correlations of our different meteorological factors with RSSI and PRR shown previously, it is clear that temperature and absolute humidity shows the strongest correlations out of the four. Even though we measure absolute humidity, which is not directly dependent on temperature, we know that the air can hold more water at higher temperatures. Based on this we decouple the dependence between the two factors and see how they correlate with RSSI. This is done by only including the RSSI and absolute humidity values for the representative link during a specific temperature (16 °C). Similarly, also looking at the RSSI and temperature values for the representative link during during a specific absolute humidity (6 g/kg). The two fixed values were chosen since they are the most common. The result can be seen in Figure 13, where a stronger correlation to temperature during which humidity was fixed is observed with a Spearman correlation of -0.43.

Correlations for all Links: The correlations presented so far have been computed for the representative link. To show how the correlations can differ over individual links, we plot the temperature correlation for each individual link during the entire experiment and the mean PRR for that link, shown in Figure 14. Here we see a variation in correlation over the different links with a tendency towards lower correlation when the link is either very strong or very weak. The figure also shows the difference between high links, low links and mixed links. Here high links are links between high mounted nodes (see Figure 1), low links between low mounted nodes and mixed links between one high and one low mounted node.

Conclusion: When the humidity is static there is a stronger correlation in temperature to RSSI than the other way around. We conclude that for the representative link, temperature is the more dominating factor. Based on this finding, we question if there exists a causal relationship between RSSI and absolute humidity.

The correlation between PRR and temperature varies between links, but it stays negative or just around 0 for all links. Links that are either very strong or very weak show a lower correlation to temperature. This is intuitive since they maintain a stable PRR while temperature varies.

VI. Discussion

The fact that weather is such a chaotic system with many variables interacting with one another makes it challenging to study how certain factors influences link measurements. It requires a sound methodology that can obtain high-quality data. We believe that many of the contradicting results in previous work comes from this inherit difficulty of studying such a complex system. In this paper, we try to straighten out some of these contradictions by capturing many meteorological aspects and correlating them to link measurements.

We have found that temperature is the most highly correlated factor to RSSI and PRR. However, this does not imply that other factors are unimportant, since several of them can themselves influence temperature and vice versa. What is clear is the fact that the performance of an outdoor WSN most certainly is affected by, and correlated with, the meteorological conditions. This can be seen for example in the identified diurnal performance cycle and the slower moving seasonal variation.

Thus, in order to design, deploy and maintain well functioning WSNs, we need to have a better understanding of how different conditions influence performance and how it can evolve over time.

A. Suggestions for outdoor WSN designers

Based on the findings presented in this paper we have come up with the following general suggestions for WSN designers.

Node Placement: Protect the sensor nodes from high temperatures as much as possible. Preferably, place them in a shaded environment or ventilate the housing.

Data Delivery: Expect variations in PRR both during different hours of the day as well as over different weeks and months. PRR will in general better during nighttime and colder months. Do not expect that all strong links (PRR $>$ 90%) stay strong, especially over long periods of time, but that the amount of intermediate links stays about the same.

Deployment Strategies: Once deployed, monitor the network for a minimum of 24 hours to ensure that the performance measure is high enough. Get an estimate of the conditions (temperature for example) by looking at historic data to understand what the network will be exposed to.

VII. Summary

In this paper, we have deployed an outdoor WSN next to a meteorological research station collecting six months of link and meteorological measurements. We have shown general trends in the performance of the network, identifying a diurnal cycle where the network performed better during nighttime. We also observed a slower moving seasonal variation.

Furthermore we have analyzed the correlations of the four meteorological factors temperature, absolute humidity, precipitation and sunlight to the link metrics RSSI and PRR. By decoupling the temperature from humidity we concluded that temperature is the most dominant correlation factor. Based on the observed correlation between precipitation and the RSSI and PRR, we also conclude that there was no observable impact on either due to precipitation. Finally, we have shown that the correlation between temperature and PRR varies over the links in our network, but remain a negative correlation.

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