EFFECT OF RAINFALL ON LINK QUALITY IN AN OUTDOOR FOREST DEPLOYMENT

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Abstract: Existing work has shown that rainfall has an effect on link quality. Some authors report a positive effect in moist conditions, whereas others demonstrate a significant decrease in link throughput as a result of rainfall or fog. The precise cause of these variations has not yet been conclusively established. This paper reports on long term (26 day) link quality results from 12 nodes deployed in a forest. We found that rainfall has the effect of decreasing the performance of 28% of good links (classified as those having above 90% packet reception), but simultaneously increasing the performance of 34% of poor links (those having below 50% packet reception). In addition, it was found that variations in link quality persisted for a few days after rainfall. This suggests that link variations are not a result of rain induced fading, but rather due to water sitting on node packaging. We present experimental evidence which demonstrates that changes in link quality (both positive and negative) are indeed due to the presence of water, capacitively loading the antenna, altering its radiation pattern.

1 INTRODUCTION

Although there have been a number of experimental studies of link quality variation over time in a wireless sensor network, most have been over a very short time period (typically a few hours) (Srinivasan and Levis, 2006; Becker et al., 2009). Furthermore, many have involved indoor deployments, where the effects of weather are minimal (Becker et al., 2009; Wang et al., 2007; Cerpa et al., 2005). Accurate estimates of link quality are essential for the deployment of a long-lived and robust sensor network. By using link estimates, bad links can be avoided. Overall network performance can be greatly improved by choosing reliable links (Wang et al., 2007).

In particular, we are concerned with the impact that rainfall has on link performance. Some researchers have reported an improvement in link quality during moist periods (Thelen et al., 2005), whereas others have reported a detrimental effect (Anastasi et al., 2004). It is thus not clear whether rainfall is an environmental factor that should be welcomed or not.

This study was conducted in order to assess the best strategy to adopt for forwarding bulk data bundles (i.e. hundreds of kilobytes) with varying delay requirements. For bulk transfer of information, what is important is that data is sent over reliable, shortest path links to the end destination. This means avoiding retransmissions and asymmetry where possible by building and maintaining a reliable tree. Changes to the network topology can incur a very large energy cost if a node has a large volume of data that has to 'backtrack' through the tree. If a link which was previously good fails, the question is whether to delay transmission or to reroute to another node. In order to decide these questions, it is necessary to know how links vary over time, and what level of stability can be expected.

In this study, we attempt to investigate the causes behind link variation in an outdoor deployment due to rainfall. This paper presents results from an outdoor deployment in a forest environment over a period of 26 days. The quality (both RSSI and LQI) of all possible links was measured every 5 minutes. Correlations were performed with data provided by an advanced meteorological station, part of a system measuring climate change, located only 500 m away.

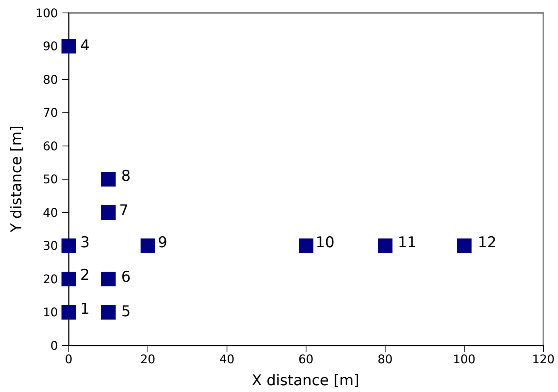

Figure 1: Layout of nodes within the deployment area.

Unlike other work, the sole purpose of this work was to monitor link quality. Thus, there are no interfering effects from network traffic or MAC layer dependencies.

2 EXPERIMENTAL SETUP

A total of 12 T-Mote SKY nodes were deployed in Wytham Woods, Oxford, from the period 17/02/2009 to 14/03/2009 (26 days). The nodes were powered by two Energizer lithium AA batteries and placed within a waterproof, protective plastic enclosure. Metal shelving brackets were used to affix the nodes to tree trunks, at an approximate height of 1.8 m above the ground.

Nodes transmit short beacons (10 bytes, including CRC) with an average period of 3 s, uniformly dithered within this period. The random number generator was seeded with the node's unique MAC ID so that nodes would not be synchronized with one another. The beacons contain the node's ID and its current timestamp. Nodes transmit the beacons at the highest power level (+0 dBm). Every 5 minutes (uniformly dithered), nodes switch to receiving mode and listen to incoming beacons for a total of 6 s. They record their own timestamp, the incoming node's ID and its timestamp, and also the LQI and RSSI as provided by the CC2420 radio. This information is stored in the 1 Mbyte external flash, and is uploaded at the end of the study. When not transmitting or receiving, nodes power down their radio modules and enter low power sleep mode.

The radio modules were configured to use Zigbee Channel 24. In the deployment area, there were no interfering WiFi signals. The layout of nodes in the deployment area is shown in Figure 1.

3 EXPERIMENTAL RESULTS

3.1 Long-term link stability

In this section we examine the stability of links, i.e. if a link that is good on a certain day, will remain good for the duration of the study. This is important for MAC protocols as it indicates the necessary frequency of route repair. The performance of every (unidirectional) link is shown in Figure 2. The average packet reception rate is indicated by the intensity of each cell, with good links represented by white and bad links represented by black. Links have been sorted according to their initial reception rates.

Figure 2 demonstrates that the majority of links, in general, show little long term variation. Some links do show significant variation, changing from very high throughput to very low throughput (e.g. link number 70). However, what is interesting about the diagram of evolution is that it shows that there are correlated variations in link performance, e.g. on February 23 there is significant variation across all links. A similar pattern is seen around March 4. This suggests that there is some common effect which is affecting all links. Note however that the variation is not all in the same direction – some links have improved whereas others have become worse. In the following sections we investigate causes for these variations.

3.2 Correlation with environmental variables

In this section, we examine the correlation of the number of good links in the network (those with overall throughput greater than 90%) with a variety of environmental variables. Data for this study were collected by an automated weather monitoring system located approximately 500 m from the deployment area. Table 1 shows the linear (Pearson's product moment) correlation coefficients for the various parameters. The results show that the two parameters which show negative significant correlation (at the 95% confidence level) are rainfall and ambient temperature. Surface wetness, which indicates the presence of water droplets also shows a negative correlation. Correlations for the other measured variables are all low.

3.3 Variation in link performance with rainfall

The previous section indicated that rainfall was the physical variable which had the strongest impact on link performance. In order to quantify the effect of

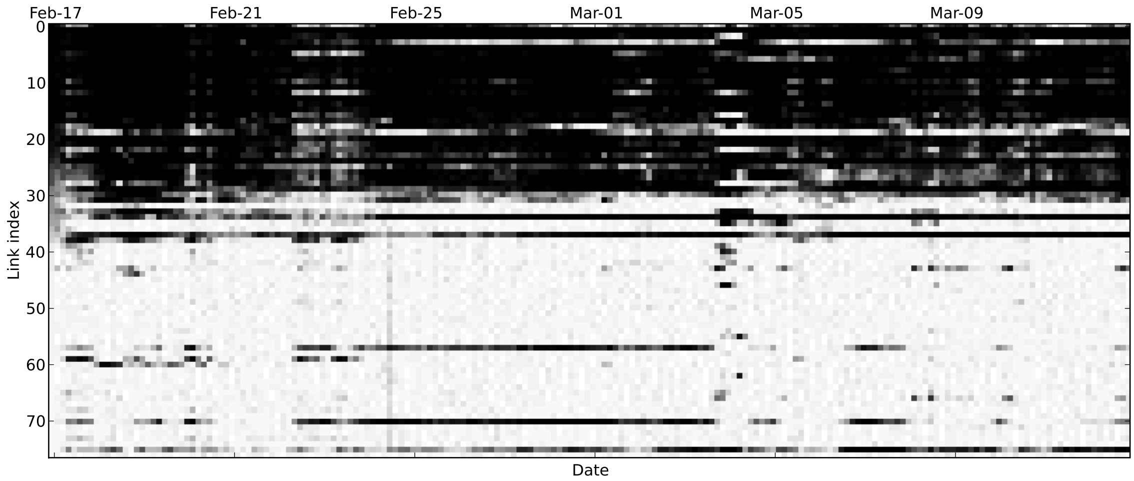

Figure 2: Evolution of links over time, using a three hour binning. The intensity of each cell represents the packet reception rate, with white representing 100% and black 0%. Links have been sorted according to their packet reception rate in the first three hours of operation, with bad links at the top of the figure and good links at the bottom of the figure.

Table 1: Correlation coefficients

Solar radiation	0.056
Net radiation	-0.033
Relative Humidity	-0.068
Ambient Temperature	-0.247
Wind Speed	-0.008
Rainfall	-0.291
Albedo (Sky)	0.056
Albedo (Ground)	0.069
Surface wetness	-0.154

rainfall on link stability, we characterized links on March 1 into categories based on their throughput. Good links are those with a throughput of over 90%, whereas poor links are those with a throughput lower than 50%. Fair links are defined as those with a throughput between 50% and 90%. The purpose of this investigation is to determine the effect of rain on different link categories.

The variation of good links over time is shown in Figure 3. This shows that on the onset of rainfall on March 3, 27.5% of links which were good on March 1 became poor or fair. Note that links did not instantly become good again once the rain had stopped. By March 6, all links are back to being good again. When it rains again on March 7, 10% of links degrade in performance to become fair.

The variation of poor links over time is shown in Figure 4. This shows that rainfall has the effect of actually *improving* link throughput, as evidenced by the fact that 37.5% of poor links have become fair in performance. Similar to the behaviour of good links, by the 6 March, all but one link has returned to poor performance.

3.4 An investigation into rain-induced fading

The correlation results show that there is a negative correlation between precipitation and link success. The results from Section 3.3 demonstrate that some links improve, whereas others become worse. We first investigate whether this variation could be due to fading caused by rainfall itself. An approximate empirical relationship between attenuation A and rainfall rate R is given by

$$A = \alpha R^{\beta} \qquad (1)$$

where α and β are parameters that are dependent on frequency and temperature (Olsen et al., 1978). A number of models provide values for these parameters depending on weather conditions. The path loss at 2.5 GHz under extreme rain conditions of $R = 250$ mm/hr, using the worst case thunderstorm distribution of Joss et al. (J-T), is calculated to be 0.124 dB/km ($\alpha = 1.63 \times 10^{-4}; \beta = 1.2$). With a maximum link range of 100 m, the expected path loss due to rainfall is negligible at 0.01 dB. It should be noted that higher frequencies (e.g. 10 GHz and above) suffer

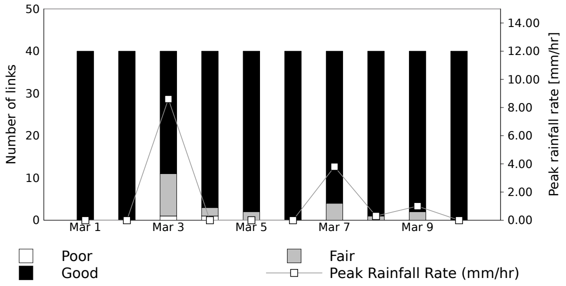

Figure 3: Evolution of links which were classified as good on March 1. Notice how the number of good links decreases greatly with the heavy rain on March 3.

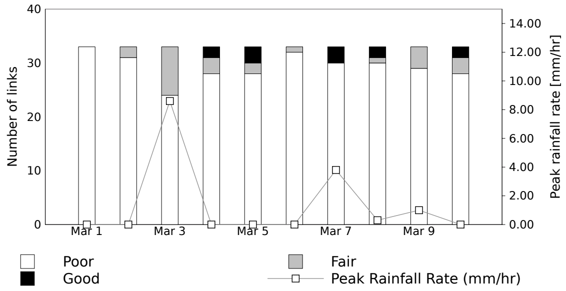

Figure 4: Evolution of links which were classified as poor on March 1. Notice how the number of fair links rises with the heavy rain on March 3.

heavily from rain fading and this attenuation is actually used in weather radars to measure precipitation rate and rainfall drop size (Meneghini and Nakamura, 1990).

However, there is a clear rain related variation in link quality, one which has been reported in other work (Thelen et al., 2005). As this loss is not due to the channel itself, there has to be another cause. As we were using the onboard antenna, we conjectured that this variation in link performance could be due to water pooling on top of the plastic enclosure, creating a reflective plane. Water has a relative static permittivity (ε_r) of approximately 80. This would have the effect of altering the antenna radiation pattern which could account for these changes.

In an attempt to determine if this could indeed explain the significant variations in link quality, we conducted a simple experiment, the details of which are described in the following section.

4 IMPACT OF SURFACE WETNESS ON RADIO PROPAGATION

The deployment demonstrated that there was a causal link between precipitation and link quality. However, this effect could not be ascribed to path loss, as attenuation by rainfall at 2.4 GHz was shown to be negligible. To investigate the effect of water droplets present on the plastic enclosure, two nodes were placed 10 m apart in a laboratory environment. One node (within a plastic enclosure) was placed on the ground and configured to transmit beacons every 0.5 s. The other node was connected directly to a PC and used to log the RSSI of the incoming beacons. Water was sprayed gradually onto the plastic housing of the transmitting node over a period of 10 minutes.

In order to indicate moisture presence on the enclosure, a simple moisture sensor was fabricated from a small piece of perforated prototyping board. The resistance of this device indicates the presence (low resistance) or absence of water (high resistance). The output from a potential divider with the sensor connected to ground and a 10 kΩ resistor connected to the 3V supply was applied to the ADC0 input of the T-Mote SKY. A threshold ADC reading was chosen which allowed the sensor to report the presence or absence of moisture.

The results from this experiment are shown in Figure 5. Initially, the RSSI level is -77 dBm. At time t = 100 s, water was sprayed on the plastic enclosure. Every further 60 s, more water was added. The RSSI plot demonstrates that the addition of water first has the effect of increasing the received RSSI by approximately +4 dB. However, as more water is added, the RSSI decreases below its original value by approximately -6 dB. Overall, this is a 10 dB variation in signal strength.

5 DISCUSSION OF RESULTS

These results show that the presence of water on the plastic enclosure has the effect of altering the received signal strength. However, this variation can be positive or negative, depending on the amount of water present. Water, with its high dielectric constant, alters the radiation pattern of the antenna, essentially acting as capacitive loading. Large amounts of water in close proximity to the antenna have the effect of detuning it, reducing its efficiency. These results demonstrate that signal strength variation is due to the presence of water on the enclosure, not channel attenuation due to precipitation. As condensation can occur on nodes without rain falling (e.g. dew), precipitation is thus not the only indicator of channel varia-

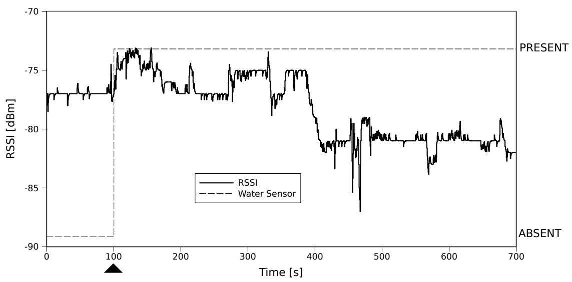

Figure 5: Experimental results demonstrating variation in RSSI with water presence on plastic enclosure. At 100 s, water was sprayed on the plastic housing. Approximately every 60 s thereafter, more water was added. Note how the received signal strength initially increases and then decreases once a large amount of water is present. Node separation was approximately 10 m in a laboratory setting.

tion.

Due to the causal link between water on the enclosure and channel variation, it would be beneficial for nodes to be able to measure this presence. Nodes could then take informed decisions as to the cause of a link failure/improvement. We presented a simple moisture sensor based on measuring the resistance between two electrodes. This method however has the drawback that the sensor needs to be mounted on the exterior of the box. Due to the presence of water, corrosion of the electrodes will occur over time. To some degree this can be lessened by applying an AC drive current to the sensor. A better method of measuring water presence would be to place two parallel plates to the interior of the enclosure and measure the capacitance. Water present on the exterior of the box will increase the capacitance. This would be a much more robust technique, as the sensor element is not exposed. Some microcontrollers even incorporate a module for measuring capacitance e.g. the Charge Time Measurement Unit (CTMU) of the PIC24F series of microcontrollers (Microchip,), allowing accurate measurements to be made without requiring external components.

As identified above, links vary in different ways according to the presence of water. In a delay-tolerant network setting, nodes can defer exchange of bulk data until conditions are favourable for network transmission. This can save considerable energy, by avoiding lossy links. To learn this information, periodic probe packets can be sent, and the relationship between link quality and surface wetness modelled at each node. This could easily be done using a simple histogram, but a polynomial model relating link quality to wetness could also be utilized.

6 RELATED WORK

One of the major investigations into channel propagation in outdoor wireless sensor networks was conducted in potato fields (Thelen et al., 2005). Mica2dot nodes were used, with external whip antennas with a transmission frequency of 433 MHz. The authors found that transmission was better during conditions of high humidity, such as overnight and during rainfall. They speculated that the cause for this could be reflection from the vegetation canopy, but did not conduct further experiments to investigate whether this was in fact the cause for variation. Another study which used both Mica and Mica2dot motes, this time operating at 868 MHz, found very significant reductions in transmission range, a reduction from 55 m to 10 m, during rain and fog (Anastasi et al., 2004). However, no details were given on the amount of rainfall or the duration of the reduction. The authors state that attenuation of the electromagnetic wave is due to absorption by water particles, but provide no validation of this claim.

There is a much larger body of work which reports on link quality in an indoor setting. The work in this paper has considered link variations over long periods of time (hours), whereas short term link estimation (milliseconds) is considered by (Becher et al., 2008) and in (Cerpa et al., 2005). Short term estimation also requires frequent probe packets. An alternative approach to link estimation is link characterization which uses bounds on link metrics instead of instantaneous measurements (Lin et al., 2008). In a much more detailed investigation, a similar approach is specified in order to estimate link quality based on probe packets sent at the start of the deployment (Meier et al., 2008). Over 8 million packets were recorded for each trial. A supervised learning technique for classifying links is presented in (Wang et al., 2007).

7 CONCLUSIONS

In summary, we have demonstrated that there is a relationship between rainfall and link performance. This is a result which has been reported on in other work, but the causes of this variation have not yet been adequately explained. We showed that the actual factor which alters link performance is not rainfall itself, but the presence of water on the exterior of the enclosure. This explains why links take time to recover from a precipitation event as they slowly dry over time. Water capacitively loads the antenna, which alters its radiation pattern. In some instances links become worse, but poor links can also improve in performance. It is a simple matter to equip a node with a sensor that can measure the presence of water. This information can be used by the MAC and networking layers to take informed decisions about routing and link management.

Based on our initial investigation, we plan to incorporate capacitance based moisture sensors in a further deployment, and to use knowledge of moisture to influence routing. We also intend to investigate whether external antennas suffer from water presence to the same degree.

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