An Experimental Evaluation of Temporal Characteristics of Communication Links in Outdoor Sensor Networks

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ABSTRACT

The packet delivery performance of outdoor sensor networks has been shown to be both unreliable and unpredictable. In this paper we study the temporal characteristics of sensor network communication links using data from three experiments running for five to twelve days in an unattended, outdoor environment. We identify significant variations in packet delivery performance over time and between links, although the overall delivery of data by the network is fit for its purpose. We evaluate the implications of our findings for the design of reliable and robust sensor network protocols.

General Terms

Performance, Experimentation, Reliability

Keywords

Packet Reception Rate, Performance Measurement, Sensor Networks

1. INTRODUCTION

A typical environmental monitoring sensor network consists of many sensor nodes, deployed across a landscape, sensing real world phenomena and forwarding observed measurements back to base stations or user gateways. Despite significant efforts in protocol design for sensor networks, field trial performance has been disappointing, with data delivery proving to be both unreliable and unpredictable [3, 6, 10] Understanding the patterns of communication failure, and their implications for protocol design is, thus, a critical step in making sensor networks more reliable and robust in practice.

To accomplish the goal of reliable and robust sensor networks, we need to thoroughly understand the variation of link quality in sensor networks operating in real world environments. Previous work on sensor network link quality is focussed on *spatial* properties such as the effect of distance on reception rates [4, 11]. Most previous experiments have been run in indoor environments over short time periods [5]. The main contribution of this paper is the measurement and analysis of *temporal* variations in link quality over time scales of days for outdoor environment monitoring networks.

In order to evaluate temporal variations in link quality, we deployed a simple single-hop wireless sensor network using CSIRO Fleck motes [9] in an outdoor environment. We measured reception rates for packets transmitted by two sensing nodes to a base station. Nodes transmitted both information about soil moisture and temperature, and also health messages, giving their on-board temperature and battery energy. We have analysed the packet reception behaviour of the nodes for possible patterns over time and correlations between links. Our main findings are that there is significant variation over time in the quality of sensor network links, that is related to nodes' position in the environment and weather conditions, but despite this there is little correlation between the performance of different links in the same area. The implications of our findings for protocol design are also evaluated.

2. RELATED WORK

To improve the reliability of packet transmission over unreliable wireless links it is necessary to study the characteristics of those links. Most previous studies focus on the spatial characteristics of wireless links [4, 11, 6].

Zhao *et al* [11] analyzed the characteristics of the packet delivery at physical and medium-access layer over indoor, outdoor and habitat environments. They showed that there is a *grey area* within the communication range of nodes in which the reception rate varies dramatically, and that physical layer coding schemes cannot reduce this unreliable grey area. Cerpa *et al* [4] measure the connectivity between nodes for two hardware platforms, Mica and Mica 2, in three different environments. They showed that small variations in node attenuation can affect the reception rate and hardware calibration between nodes results in link asymmetries. Falsio reports similar experiments [6], but includes outdoor tests showing that the communication range of motes falls significantly in periods of fog and rain.

A study of temporal properties of low power wireless links is reported by Cerpa *et al.* [5]. Experiments were conducted in an indoor office-like setting lasting at most 4 days. They concluded that the global quality of the bandwidth of the system has very little oscillation over time, and good quality links tend to be very stable over time, which is similar to the results in [4]. Lal *et al*[7] report an experiment to monitor the wireless link variation between a transmitter and a receiver for several days in an indoor environment. They measured signal to noise ratio (SNR) and packet success rate (PSR), and showed that values are similar at the same time on different days. Also, when the SNR is above 11dB, then the PSR and SNR can be used as a cost metric for link quality.

Aguayo *et al*[2] analysed the cause of intermediate packet loss in Roofnet, an outdoor multi-hop wireless network. Unlike previous work measuring indoor environments, their study showed that loss rates in an urban, outdoor setting were independent of both link distance and signal-to-noise ratio. They also studied the delivery probability changes at a time scale of 200 milliseconds and observed that most links have relatively stable loss rates over time, and the loss behavior of different links could be considered independent when the time intervals are very small (less than 0.1 seconds).

In this paper, we also perform experiments to analyse the temporal characteristics of wireless links. There are three major differences between our experiments and previous work. The first is our experiments were performed in an unattended, outdoor environment. The second one is our experiments were run over longer time scales than previous work. In previous work, experiments lasted 4 days at most, but our experiments ran from 5 to 12 days each. Finally, we sent not only data packets but also health packets, including information of on-board temperature and battery voltage, to analyze link performance.

3. EXPERIMENTAL METHODOLOGY

We have implemented a single-hop wireless sensor network using CSIRO Fleck motes to study packet reception rates. The experimental set up is representative of real outdoor environmental monitoring applications [3, 10]. The Flecks use the Atmel Atmega 128 processor (same as Mica 2) and run the Berkeley TinyOS operating system. The Nordic NRF903 radio chip used for communication achieves ranges up to 500m in open outdoor environments and a solar battery recharger is included on the main board. We used two nodes (Fleck 16 and Fleck 149) and one base station to construct our experiments in an outdoor park. Each node gathered data from soil moisture and soil temperature sensors. Fleck 16 was approximately 10 metres from the base station in a relatively open area, and Fleck 149 ***[was]*** approximately 20 metres away and close to trees and bushes. Both nodes were shaded by trees for part of the day, but in full sun for long periods. We collected three types of data:

Soil Data: soil moisture and soil temperature readings;

Health Data: on-board temperature and battery voltage.

During the experiment, each node transmitted a burst of three packets (two soil and one health) every 5 minutes. Received packets ***[are or were]*** recorded by the base station. We performed the experiment three times lasting 5.5, 6.5 and 12 days respectively. The following sections report our results on the temporal link quality of the wireless sensor network.

4. TEMPORAL PROPERTIES

In this section, we analyze the links between each sensor node and the base station. Our goal is to understand characteristics of links in deployed sensor networks, to identify factors which affect the link quality and so to improve network protocol design. There are many factors that affect packet delivery in wireless communication systems: environment, battery energy, network topology, and traffic patterns. It is hard to separate these factors in order to study the impact of any one specific factor on packet delivery performance. In this paper, we focus on packet delivery performance over time. We investigate whether there are predictable patterns for link quality over time, and whether we can use these patterns to improve the performance of network protocols.

Table 1: Packet Reception Summary

Node	Trial	Mean	Median	Max	Std Dev
16	1	49.16%	58.33%	100%	29.43%
149	1	16.96%	13.89%	77.78%	13.29%
16	2	16.61%	4.167%	83.33%	21.52%
149	2	13.23%	8.333%	52.78%	14.60%
16	3	42.94%	48.61%	97.22%	30.75%
149	3	6.559%	2.778%	47.22%	8.885%

Table 2: Average Packet Reception Rates for Day and Night

Flecks	Time	Mean	Std Dev
Fleck 16	Day	29.97%	22.56%
Fleck 16	Night	46.98%	19.60%
Fleck 149	Day	16.03%	8.64%
Fleck 149	Night	9.287%	5.93%

4.1 Packet Delivery Performance

Our basic metric for packet delivery performance is *packet reception rate*: the ratio of received packets to packets transmitted over a period of time.

We calculate the average packet reception rate over an interval of one hour. Since each node sends 3 packets every 5 minutes, the base station should receive 36 packets within 1 hour to achieve a 100% reception rate. Figure 1 illustrates the packet reception rates in three trials, each measured from 0:00am, and running from 23 November 2005 to 28 November, 02 December to 08 December, and 22 December to 02 January 2006 respectively.

Figure 1 and Table 1 both show that the packet delivery performance of Fleck 16 is better than that of Fleck 149 in all three trials, although the poor performance of both nodes is similar in trial 2. Possible reasons for the poorer performance of Fleck 149, include its site amongst trees and bushes, and its greater distance from the base station than Fleck 16.

Figure 1 suggests that there may be a periodic pattern to packet losses, and so we compared the average performance of each fleck in the day time and night time. Figure 2 shows the reception rate of each fleck averaged over day time hours (7:00 to 18:00) and night time hours (19:00 to 6:00), where sunrise is around 6:00 and sunset around 19:00. Table 2 summarises these results, confirming that the average performance of Fleck 149 is better in the day than at night, and on the contrary, Fleck 16 performs better at night than in the day. The environment of trees and bushes around Fleck 149 may create a more humid environment at night, so decreasing packet delivery success. Fleck 16 may be affected by cars, machinery or other site noise during the day that is

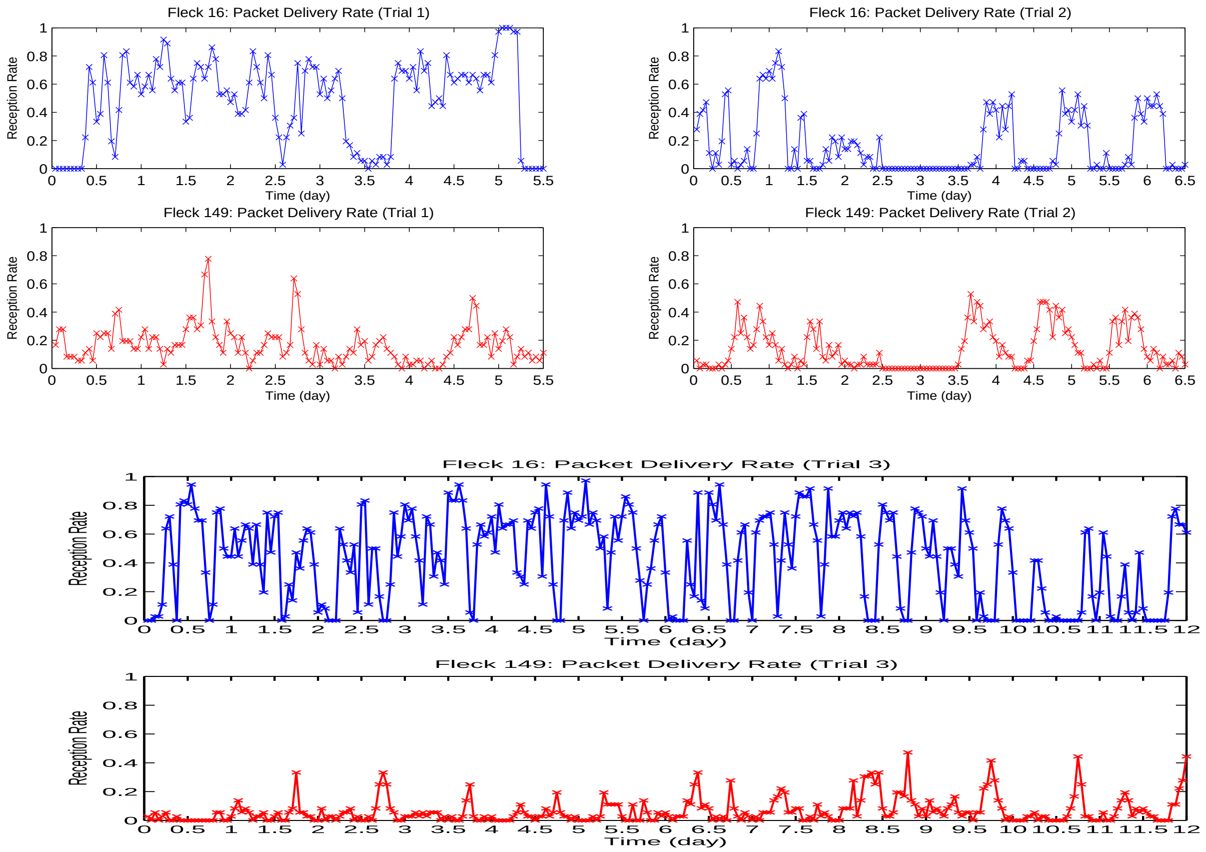

Figure 1: Packet Reception over Time

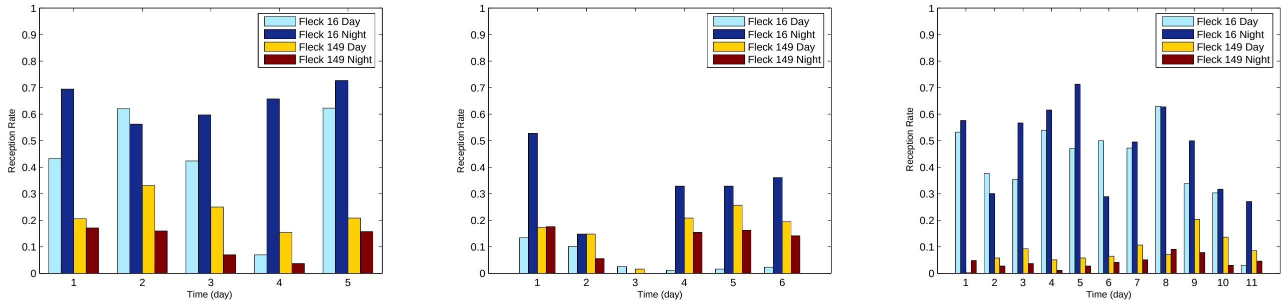

Figure 2: Reception Rates by Day and Night

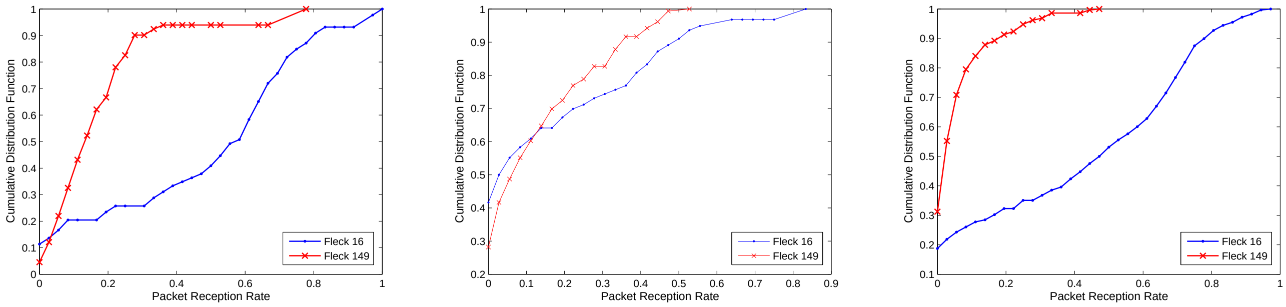

Figure 3: Cummulative Density Functions of Packet Reception Rates

not present at night.

Having considered average performance for each fleck over time, we now look at the distribution of reception rates. Figure 3 shows the cumulative distribution function (CDF) of each node's packet reception rate. That is, $F(x)$ is the probability of observing a reception rate less than or equal to x. The probability of receiving no packets (that is, observing a packet reception rate equal to 0) is about 10% for Fleck 16 and 5% for Fleck 149 in trail 1, 40% and 30% respectively in trial 2, and 20% and 30% in trial 3. A large proportion of packets are delivered when the reception rate is low for Fleck 149. For example, in trial 1, about 90% of Fleck 149's packets are received when the reception rate is less than 30%. In the same trial, only 20% of Fleck 16's packets are received when the reception rate is less than 30%. Each trial shows significant differences between the CDF in the middle phase. At high reception rates, the trend of these two curves are similar, but the maximum values differ: the packet reception rate of Fleck 149 never reaches 100 percent.

There are several conclusions we can draw from our analysis. First, the link quality of Fleck 16 is much better than that of Fleck 149. Where there is a choice of transmitters, Fleck 16 should be chosen in preference to Fleck 149. Second, the times of good delivery performance for each of the two Flecks is quite different. For Fleck 16, its performance at night is better than in the day; while on the contrary, the performance of Fleck 149 in the day is better than at night. To achieve higher delivery success we could, for example, stop Fleck 149 at night but let it send more packets in the daytime, and adopt the opposite strategy for Fleck 16. Third, Fleck 16 and Fleck 149 have almost the same periods of bad quality links, but their medium quality links have quite different performance. So we should carefully select nodes to transmit packets when link quality is medium. In our network, Fleck 16 should be selected to send more packets than Fleck 149 during periods of medium quality reception.

4.2 Link Correlation

The results presented in Section 4.1, suggest that the performance of the links between flecks 16 and 149 and the base station are not correlated when we consider performance averaged over day and night times. In this section, we further examine if there is any *temporal correlation* of packet reception rate between two different links. If the packet reception rate of two links is highly correlated, then different links have the similar performance at any given time, and so there is little benefit in changing links. If, on the other hand, link performance is not correlated, then we can improve performance by changing from one link to another when performance deteriorates. Most fault tolerant protocols proposed for sensor networks assume the poor performance of different links is not correlated, and so it is almost always possible to transfer traffic from a bad link to a better link.

The packet reception correlation coefficient between two links, Fleck 16 (a) and Fleck 149 (b), is defined by:

$$R_{a,b} = \frac{\sum_{k=1}^{n} x_{a,k}x_{b,k} - n\overline{x}_a\overline{x}_b}{[\sum_{k=1}^{n} x_{a,k}^2 - n\overline{x}_a^2]^{1/2}[\sum_{k=1}^{n} x_{b,k}^2 - n\overline{x}_b^2]^{1/2}}$$

$x_{a,k} = 3$, $x_{a,k} = 2$, $x_{a,k} = 1$ and $x_{a,k} = 0$ represents that three, two, one and zero of the three packets sent by a fleck are successfully received by the base station in the kth time slot. $\overline{x}_a$ and $\overline{x}_b$ is the average reception rate over the selected time window. In our paper, we calculate the correlation of 3 trials in the whole running time window.

Table 3: Correlation in 3 Trials

	Trial 1	Trial 2	Trial 3
Correlation	0.0374	0.0623	-0.0677

Table 3 shows the correlation values in our three experiments. We can clearly see that there is almost no correlation between two links in our all three trials. An interesting phenomenon is two links in trial 3 has a weak negative correlation. That means when the link of Fleck 16 to the base station has a good quality, the link of Fleck 149 to the base station has a bad quality, and vice versa. But in Trial 1 and Trial 2, they both have weak positive correlations. Thus it is hard to predict the link quality and opportunistic routing [8] is a better choice than link state routing for outdoor sensor networks.

4.3 Environmental Conditions

In this section, we consider whether environmental conditions, such as climate, could influence the packet reception rates. From Figure 1, we can see that the link quality during trial 2 is worse than trials 1 and 3, and includes a significant period (over 24 hours from day 2.5 to 3.5) in which no packets are delivered. Bureau of Meteorology data [1] for the trial period shows small rainfalls of 0.4mm and 1.4mm during days 2 and 3 of trial 2 (4th and 5th of December). These were the only trial days with rain. Similar significant drops in effective transmission distance were observed in reception trials with Mica2 and MicaDot motes measured during fog and rain in Italy [6].

Figure 4 illustrates on-board temperature and battery voltage for the two sensing flecks during trial 3. Fleck 16 uses a Lithium 3.7V battery with 2200mAH. Fleck 149 uses 3 AA size NiMH batteries with 2300mAH. Both nodes have a small 6V solar panel to recharge the batteries. We observe that the battery voltage of Fleck 149 is lower at night than in the day, while the battery voltage of Fleck 16 is higher in the day than the night. However, since both batteries are almost fully recharged each day, these differences between the batteries are unlikely to impact packet delivery performance. However, the battery voltage of Fleck 16 is decreasing over time, while that of Fleck 149 is more stable. We believe this is a property of the battery chemistry: NiMH batteries show almost full power until suddenly falling at the end of their life, whilst Lithium batteries show a smoother decrease throughout their lifetime. If so, then it is possible that neither battery is being fully recharged each day, and that we need to use higher power solar cells, or reduce the duty cycle of the nodes. The latter is certainly feasible, since the trial application both used a more frequent reporting period (5 mins) than required in the field, and also allowed generous intervals of radio-on time for reprogramming the Flecks over their wireless links.

We draw some conclusions from our analysis of health data from the flecks. First, rain directly affects the link quality of wireless communication: link quality is low when the environment is raining. Second, battery performance may vary because of differences in solar recharge opportunities and for different battery chemistries. We need to optimise these characteristics in order to improve the performance of

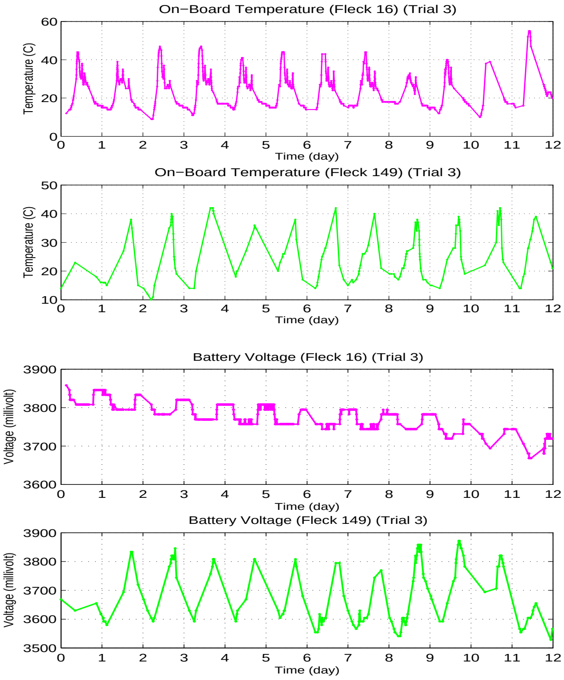

Figure 4: On-Board Temperature and Battery Voltage

wireless networks.

5. CONCLUSIONS

In this paper, we analyse the temporal characteristics of sensor network links based on outdoor experiments in a realistic setting over five to twelve days. What are the implications of our findings for sensor network protocol design? First, our results support the use of opportunistic routing strategies [8] to mitigate the effect of varying channel conditions; Second, our results explain the failures observed in realistic outdoor wireless sensor network environments when using traditional protocols that re-transmit each packet up to a preset maximum number of times, with or without acknowledgement [3, 10]. These protocols are not sufficiently adaptive for outdoor sensor networks and can waste considerable energy. Third, weather conditions such as rainfall and humidity, and hours of sunshine certainly influence protocol performance and reliability. It may be useful for protocols to use such information to predict good transmission times, or avoid bad ones. Finally, it is important to note that although the overall packet delivery performance in this trial was low, that the data delivered was *fit for purpose* in that most trends of each measured variable (soil moisture, temperature, battery voltage and onboard temperature) could be clearly seen in real time as the data was gathered in to a web visible database. Furthermore, since our nodes also log their gathered data to onboard flash memory, it is possible to reconstruct any missing sections of data, either at the end of the trial, or by querying nodes during reliable transmission periods. Best effort data delivery, coupled with reliable back-up by local logging, is sufficient for many environmental monitoring applications. Instead of focussing on fully reliable wireless transmissions, attention is needed to ensure the quality and reliability of the sensor readings themselves. In future work, we plan to implement adaptive routing protocols for environmental monitoring, based on the results of our studies of the characteristics of wireless communication links in the field.

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