Experimental Evaluation of Temporal and Energy Characteristics of an Outdoor Sensor Network

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Abstract

This paper revisits the link quality issue in Wireless Sensor Networks (WSN) by studying the temporal and energy characteristics of a 2.4Ghz sensor network in an outdoor environment. Using different values of output power and sampling period, we analyze battery behavior in motes placed at different distances and show that farther motes have a shorter battery life. Our experimental results suggest that when deployed in real world deployments, the sampling periods of sensor networks be adjusted according to distance to normalize battery lifetime and a more accurate energy-aware routing protocol be developed.

Categories and Subject Descriptors

C.2.1 [COMPUTER-COMMUNICATION_NETWORKS]:  
Network Architecture and Design, Wireless communication

General Terms

Measurement, Performance

Keywords

Performance, Wireless Sensor Network, Battery, Link Quality

1. Introduction

The emergence of WSN as one of the dominant technologies in the coming decades has posed numerous unique challenges to researchers. These networks are designed to be composed of hundreds, and potentially thousands of small smart sensor nodes (called motes), functioning autonomously and self-organizing in a mesh-type network. When working with real-world deployments many new issues arise: Wireless links are unreliable and unpredictable, link quality varies in time, and motes need to be battery powered to run unattended for months or even years.

To implement reliable and robust sensor networks, we need to understand the variation of link quality and battery behavior in a real world environment. Low-power transmitters have a limited range, and it is important to understand communication patterns. Energy is the scarcest resource of WSN motes, and it determines the lifetime of WSNs. Motes are meant to be deployed in various environments, including remote and hostile regions; consequently, they must use little power and one need to make sure that all batteries last the same amount of time. Also, battery level has an impact on routing: Packets should be sent to motes with a higher battery level.

1.1 Related work

Previous studies on temporal models of radio propagation were carried out with a specific emphasis on the variability of Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI) in respect to a particular location as well as the determination of the so-called “gray area”, a region in which the packet loss rate varies considerably.

There have been many studies with deployments in various environments using low-power sensor motes [1, 2, 3, 4, and 5]. Most of these experiments used the TR1000 [1] and CC1100 [2] low power RF transceivers which are used by Mica 1 [3] and Mica 2 [4] motes respectively. Zhao et al [5] performed a temporal analysis of packet delivery in a dense sensor network deployment of motes placed in a straight line. They revealed heavy variability in packet reception rate (PRR), and showed the prevalence of the “gray area” within the communication range of sensor radios, and indicated significant link asymmetry. Reijers et al. [6] performed further investigation on the “gray area” and the environmental effects on the links. Their results showed that it was much less pronounced in the outdoor and open space environments than in the corridor but that it was perceptible. They interpreted this outcome as a result of the indoor multi-path effects.

Cerpa et al. [7] used two different hardware platforms consisting of Mica 1 and Mica 2 motes to perform experiments in three different environments under systematically different conditions. Among other things they concluded that there was no clear correlation between packet delivery and distance in an area of more than 50% of the communication range. Moreover, Aguayo et al. [8] performed some measurements on a 38-mote urban 802.11b mesh network. They found that link distance and S/N ratio had an effect on loss rates. They added that the correlation was weak.

Woo et al. [9] measured the PRR against the distances in a uniform grid WSN. They discovered that both the mean link quality and the variance in quality were a function of distance. Ganessan et al. [10] studied temporal behavior of a large-scale WSN (over 150 motes) in an obstructed parking lot at various transmission power settings. They focused on the packet delivery rate and link asymmetry at both the link and MAC layers. They presented statistics on PRR, effective communication range and link asymmetry at the data link layer.
Srinivassan et al [11] conducted an evaluation to compare RSSI and LQI with second generation chips (CC2420). Their preliminary results indicated that RSSI for a given link had very small variation over time for a link. Also, the results showed that when RSSI was above the sensitivity threshold (about -87 dBm), the PRR was at least 85%. On the other hand, the results showed that LQI varies over a wider range over time for a given link (and that the mean LQI computed over many packets results in a better correlation for PRR).

Lal et al [12] state that an immediate marker of link quality is Signal to Noise Ratio (SNR). They define a good channel as one that has SNR greater than 25db for the most part of the observation period (one day), a moderate channel as one where SNR fluctuates between 25dB and 15dB. If SNR is less than 15 dB most of the time, then, they call it a bad channel.

1.2 Contributions and outline
We performed experiments to measure the variability of wireless links and to analyze the behavior of Sun SPOT mote battery in different conditions. Building upon a routing scenario where the different motes placed in the sensing environment are communicating with a base station unit in a single-hop network topology, we measured signal level, link quality and battery level for packets transmitted to the base station. We calculated the PRR and analyzed its relation to signal level and distance. Our experimental results revealed that (1) there is variation over time in the quality of WSN links (2) the link quality is related to motes positions and (3) battery life is also related to the position of the motes as well as to the sampling period and the output power. These findings suggest that when deployed outdoor, the sampling period of WSN be adjusted according to distance to normalize battery lifetime and a more accurate energy-aware routing protocol be developed.

The main differences between our work and previous studies are threefold. First, to the best of our knowledge, none of previous studies analyzed the temporal characteristics and battery behavior of 2.4Ghz WSN in an outdoor environment like in our work. Wireless motes that operate on the 2.4Ghz frequency band provide the potential to be used all over the world, since it belongs to the ISM (industrial, scientific and medical) internationally reserved radio bands. Secondly, while most of previous experiments were conducted indoor, our experiments were performed in an unattended outdoor environment. Finally, in contrast to previous studies, our experiments were carried out a week each until all of the motes had depleted their batteries to measure their lifetime.

The remainder of this paper is as follows. Section two presents our WSN setup. Section three details our experimental settings while our conclusions and future work are reported in Section four.

2. Experimental settings
This section describes the WSN test-bed used for our experiments. First, we describe the Sun SPOT motes and their characteristics, and then illustrate the environment where the tests have been carried out.

2.1 Experimental platform
As illustrated by Figure 1, Sun SPOT (Sun Small Programmable Object Technology) motes are shipped from the manufacturer with 3 components: (1) a sensor board (2) a processor board and (3) a battery. Each Sun SPOT mote comes with a 180 MHz 32-bit ARM920T core, 512K RAM, 4M non-volatile Flash memory, 802.15.4 radio, 8 multi-color LEDs, and a USB interface. The default hardware configuration includes three sensors: accelerometer, temperature and light sensors. What distinguishes the Sun SPOT mote from comparable devices is that it runs a Java Micro Edition Virtual Machine directly on the processor without an operating system. A Sun SPOT kit comes with two free-range Sun SPOT motes and one base station unit. The base station unit is thiner, does not have a battery board, communicates wirelessly with the Sun SPOT and streams the data via a USB connection.

The wireless network communications uses an integrated radio transceiver, the TI CC2420 (formerly ChipCon). The CC2420 is IEEE 802.15.4 compliant and operates in the 2.4GHz to 2.4835GHz ISM unlicensed bands. The IC contains a 2.4GHz RF transmitter/receiver with digital direct sequence spread spectrum (DSSS) baseband modem with MAC support. Other features include separate TX and RX 128 byte FIFOs, AES encryption (currently not supported), received signal strength indication (RSSI) with 100dB sensitivity and transmit output power setting from -24dBm to 0dBm. Effective bit rate is 250kbps and chip rate is 2000kChips/s. Receive sensitivity is -90dBm. The antenna is a folded monopole λ/4 wave with reasonable omni directional radiation. [14]

The internal battery is a 3.7V 720mahH rechargeable lithium-ion prismatic cell. The battery has internal protection circuit to guard against over discharge, under voltage and overcharge conditions. [14]

The Sun SPOT mote drops into a power saving mode (“shallow sleep”) to reduce power consumption and extend battery life whenever all threads become idle. Considerable power can be saved during shallow sleep even though it is still necessary to power much of the hardware. Hence, the Sun SPOT can resume from shallow sleep without any latency and as soon as any thread becomes ready to run [13]. The shallow sleep power consumption mode is about 24ma [14].
2.2 Experimental setup

We used five Sun SPOT motes and one base station unit to conduct our experiments on the roof of the Forum building of the Royal Institute of Technology (Kista campus) in Stockholm, Sweden. It is an open space environment that offers a line of sight from the base station to all Sun SPOT motes. We placed the motes from 48m up to 100m far from the base station, at heights from 90cm to 277cm with respect to the base station. All the motes were in weatherproof, plastic enclosures. The attenuation of the enclosure is of about 3dB. The radio channels were selected to avoid collisions: Each Sun SPOT mote has its own time slot to broadcast within. In order to have significant results, experiments were performed over a long period of time. The base station was connected to a PC for data gathering, recording, and monitoring the link quality. Figure 2 represents a picture of the test-bed and Table 1 describes the positioning and configuration settings of the motes.

![Figure 2: Picture of the test-bed](image)

<table>
<thead>
<tr>
<th>Mote ID</th>
<th>Distance</th>
<th>Height</th>
<th>Channel</th>
<th>GPS position</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48m</td>
<td>90cm</td>
<td>2425MHz</td>
<td>N 59 24.338 E 017 56.622</td>
</tr>
<tr>
<td>2</td>
<td>58m</td>
<td>110cm</td>
<td>2410MHz</td>
<td>N 59 24.316 E 017 56.671</td>
</tr>
<tr>
<td>3</td>
<td>67m</td>
<td>182cm</td>
<td>2415MHz</td>
<td>N 59 24.345 E 017 56.655</td>
</tr>
<tr>
<td>4</td>
<td>73m</td>
<td>222cm</td>
<td>2420MHz</td>
<td>N 59 24.308 E 017 56.701</td>
</tr>
<tr>
<td>5</td>
<td>100m</td>
<td>277cm</td>
<td>2405MHz</td>
<td>N 59 24.358 E 017 56.672</td>
</tr>
</tbody>
</table>

Table 1: Positioning and configuration settings of the motes

3. Experiments

In this section, we describe different experimental scenarios and analyze the results of the experiments.

3.1 Experimental scenarios

Using five Sun SPOT motes placed at different distances from the base station unit in an outdoor environment, we conducted three sets of experiments with the expectation of evaluating the temporal link quality of the WSN and the battery behavior. The first two sets of experiments, called A and B, were carried out with a sampling period of 10 secs using an output power of -3 dBm and of -10dBm respectively. In the remainder of this paper, the set of experiments conducted under the label A (-3 dBm) are referred to as experiments with higher output power while the set of experiments referred to as B use lower output power (-10dBm). The last set of experiments, called C, was carried out with an output power of -3 dBm and a sampling period of 5 secs.

In our experiments, the base station periodically received a burst of packets from the motes (labeled from 1 to 5), which transmitted one by one, and store received packets. Each received packet contained: The mote number, a packet identification number, time expressed in msec, RSSI value, LQI value and battery level. We used off-the-shelf Sun SPOT motes. We kept the general-purpose sensor board that has the temperature, light, acceleration sensors as well as the LEDs. This might have influenced the battery consumption, but is a realistic situation.

3.2 Link Quality Estimators

Many protocols have been developed that rely on metrics representing the reliability or goodness of the links. The procedure for selecting the metric to be used for the experiment is very important and has a direct impact on the accuracy of the link performance measurements. The most commonly used link quality estimators are the RSSI (Received Signal Strength Indicator), the LQI (Link Quality Indicator) and the PRR. RSSI is a signal-based indicator, and is computed over the signal present in the channel at a particular time. In case of interferences, RSSI boosts while received packets decrease. Also, it has been shown that LQI has a better correlation with PRR, but only if computed over an averaged number of packets. However, the correlation gets worse as the window number of packets over which PRR is computed decreases. Therefore, when using an estimate based on multiple packets is necessary, it is always advisable to adopt the PRR.

In the Sun SPOT mote, the RSSI ranges from +60 (strong) to -60 (weak). To convert it to decibels relative to 1 mW (= 0 dBm), one has to subtract 45 from the measured RSSI value, e.g. for an RSSI of -20 the RF input power is approximately -65 dBm. The LQI ranges from 0 (bad) to 255 (good)

3.3 Link Quality over time

We know that link quality is not stable over long time periods. Also, the behavior changes depending on the link considered. We measured the LQI for the five motes, and the corresponding results for the experiment A are shown in Figure 3. Time is represented on the horizontal axis and covers a period of approximately seven days. The vertical axis shows the LQI behavior obtained by averaging 50 values. The results show that LQI has a different instant behavior depending on the link. LQI becomes more and more variable as the averaging window decreases because its values become more widely ranged. Also, it is not possible to define a pattern (day/night) from the LQI values. However, a performance pattern is revealed by this figure where mote number 5 performs worse while mote 1 achieves the best performance. The remaining motes 2, 3, 4 performed worse than mote 1 but better than mote 5. These results are in agreement with...
Figure 4 which reveals the evolution of the LQI with the position of the motes.

3.4 Link quality over distance
Figures 4 and 5 show the average values of LQI and RSSI for the individual motes in experiment A and B respectively. We observed that there is a linear correlation between the two estimators and the distance: both LQI and RSSI decrease as the distance to the base station increases. However, mote 4 shows an unexplained behavior. In facts, mote 4 has high average values for both LQI and RSSI than mote 2 and 3 which are both located at shorter distance length. We suspect that this result is due to the spatial placement of mote 4 which should be investigated upon in a subsequent study.

3.5 Packet Reception Rate
Figure 6 shows the relationship between RSSI and LQI and figure 7 shows the relationship between PRR and RSSI in experiments A and B. In these experiments the LQI, RSSI and PRR indicators are computed by aggregating 50 packets. In experiment A, the shape of the curve in Figure 6 is an overturned “L”, with a knee leveling as the RSSI value is ~43. This reveals that it is sufficient for RSSI to be above the radio chip’s threshold for the links to show the same LQI value. In experiment B, LQI and RSSI values are almost linearly correlated. RSSI is so low that we are in the linear part of the “L” of experiment A. Figure 7 reveals a similar performance pattern for PRR where a linear behavior appears earlier for lower output power. In experiment B, the links lying on the vertical part of the curve have a smaller number of data points because these links were so poor that fewer packets were received at the base station.

3.6 Energy properties
The motes measured their battery level over the course of the experiments which ran until the individual motes were able to communicate with the base station. It was therefore possible to both study the battery depletion behavior and to analyze its lifetime. Figure 8 shows battery level against time in experiment A. Although the batteries were charged with an external power source before the experiment, not all the batteries started with the same energy level. Also, the curve of battery discharge is different for the individual links. In particular, the battery of mote 3 shows a strange ‘step-like’ behavior that we could not explain and battery of mote 5 shows a step and is much more variable. In experiment B, the battery of mote 3 finished to work almost immediately. Figure 8 shows battery level against time while figure 9 depicts the battery level against the distance in experiments A and B. The figures show that farther motes have shorter battery lifetime, and that battery lifetime seems to be linearly dependent on the distance length. The strange behavior of mote number 3 can be seen in these graphs too: In experiment A the battery lasts longer than the other motes, while in experiment B it lasts a very short time. In experiment B, with a lower transmit output power, all the batteries seem to last the same amount of time. The batteries last a much longer time with a lower transmit output power. In experiment A, the longest living mote worked for 133 hours, while the shortest living one worked for 58 hours. In experiment B, the longest living mote worked for 108 hours while the shortest living one worked for 98 hours (excluding mote 3).
These results reveal that when defined by the lifetime of its shortest living mote, the lifetime of a WSN is higher under lower transmit output power.

We conducted another experiment C (not illustrated using a figure for space limitation) where we investigated how the battery lifetime depends on the sampling period. We observed that using a sampling period of 5 secs instead of 10 secs reduces the battery lifetime. The longest living mote worked for 72 hours (mote 3), while the shortest lived for 68 hours (mote 2). This suggests that the sampling period can be adjusted in order to have the same battery lifetime for all motes located at different distances from the base station.

4. Conclusions

We investigated the performance of link quality in WSN over time. We observed that it’s related to the motes location by distance. Moreover, the battery lifetime duration is related to the location of the motes by distance as well as to the sampling period and the output power.

We found that the link quality varies over time and that PRR and RSSI are correlated. More interestingly, we discovered that LQI depends on the distance length and that the battery lifetime depends on the distance in a quasi-linear way using high power. Also, we studied the dependency on output power and on sampling period. In conclusion, we foresee several interesting applications as results from our findings. These include the development of a battery-level aware routing protocol for real-world WSN applications where (1) the sensor motes are deployed with a careful selection of the sending output power and (2) the motes closest to the base station are sampled more frequently than those located farther away from the base station. Comparing the link quality of the Sun SPOT motes to the link quality provided by other types of motes such as the open sensor motes SquidBee [15] is an extension to the work presented in this paper. Finally, this study was done in the context of a single-hop WSN, hence the generalization of the link quality in single-hop WSNs to multi-hop WSNs is another avenue for further research work.

REFERENCES