Channel-Specific Wireless Sensor Network Path Analysis

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Abstract

Channel-specific path data for a 46-node 2.4 GHz sensor network deployed in an industrial setting is presented. Each node generates one data packet every 28 seconds with the number of transmissions, received acknowledgements, average RSSI, and other metrics for a path to a single neighbor on a single channel for every 15 minutes of operation. Four days of data were recorded, revealing the scale of time-variation of stability throughout the network and how this is a frequency-dependent quantity. Particularly on low-power paths, both RSSI and stability are observed to vary in unpredictable ways that differ from other paths in the same spatial vicinity. Channel hopping and path diversity succeed in maintaining near-perfect reliability despite this time- and frequency-variance.

1. Introduction

Wireless sensor networks operating indoors face RF propagation challenges that lead to time-varying signal and interference strength at the receiver. These effects are difficult to predict during the provisioning stage of a network, and in the field of wireless sensor networks, signal strength effects have been studied mainly with the objective of localization [1]. Multi-path effects in particular pose problems as they can have different impacts on different communication channels and can change as humans and machinery alter the RF environment. An example of the severity of multi-path effects in the 900 MHz band over the size scales of interest is presented in [2]. While predictive strategies for determining the number and location of nodes in a network exist, the actual measured performance of a well-planned network can vary significantly from what is predicted in these models. A deployment in an industrial environment [3] was measured to assess the channel characteristics of a small number of paths with the same radio hardware that we used and showed variation in path stability. Protocols such as ZigBee [4] allow for star-connected single-channel networks to be formed which can result in data loss if this variation is sufficiently large.

This paper details the first experiment, to our knowledge, to measure the real time-varying effects on different channels in a monitoring sensor network carrying actual traffic. The presented statistics are intended mainly to illustrate some of the phenomena observed in the network, but the intent is for the full set of data to be used as test input for wireless sensor network simulations.

2. Test Location

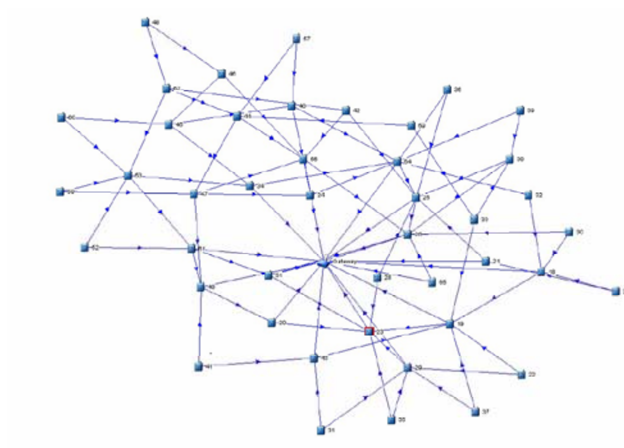

Figure 1. Multi-hop network topology. Arrows represent used paths in the network and point towards the gateway.

The network is deployed in a printing factory in Berkeley, California, and has been running for 25 days at the time of writing. The building has a rectangular footprint, measuring 250 feet x 225 feet (1.5 acres) and is three stories tall. The factory is divided into three distinct areas with different propagation obstacles. The south third contains numerous small job printing cells that process pamphlets, voting ballots, handouts and small catalogs. The central third houses the lithography and digital media center on the ground floor, with two floors of general office space above. The north third houses one large printing machine that takes 5-ton paper rolls in at one end, and pushes out completed technical manuals out

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the other end. Also in this bay are the air-handling motors for the entire facility. There are many obstacles in the work area that could impede RF communication and cause multi-path reflections, but there are no major sources of interference.

The network manager is placed on the top floor of the office section. 46 radio nodes were deployed throughout the facility, in the manufacturing areas near and around various printing machines, throughout the lithography areas, and in the office areas. The nodes report up to the network manager all the neighbors within RF range, and from those potential connections the network manager attempts to make the healthiest possible network. Many of these potential paths go unused until they are needed to repair path failures. The least connected nodes reported only 4 potential neighbors, while the most connected node reported 26 potential neighbors. The farthest nodes in the resulting self-assembled mesh network had a minimum depth of 3 hops. The average hop depth of all packets for all nodes was 2.48 hops per packet. The connectivity of the network showing only the used paths is given in Figure 1.

All nodes in the network use the same hardware and software and perform both data generation and routing functions. Nodes use the TI Chipcon CC2420 [5] radio with a power amplifier to increase output power. Output is nominal 15 dBm EIRP and shows device-to-device variation from +12 to +17 dBm at 25 °C.

3. Network Protocols

The network deployed was architected to provide high-reliability collection of periodic data from all the sensor nodes and follows link provisioning rules similar to those presented in [6]. The network is many-to-one: all data is collected at a *gateway* node which relays the packets to the manger and then to the user. The network operates using the Dust Networks Time-Synchronized Mesh Protocol (TSMP, [7]). The centrally-computed TSMP schedule dictates which of the 16 available channels as defined in the 802.15.4 PHY layer specification [4] (starting at 2.40 GHz and with 5 MHz spacing) should be used for each transaction. During a transmit slot, the transmitting node first performs Clear Channel Assessment (CCA) on the specified channel, and if it passes, transmits the packet to the waiting receiver. If the CRC of the packet passes at the receiver, it immediately sends an acknowledgement to the original transmitter on the same channel within the same 31.25 ms time slot. Every successful message pass consists of the successful transmission and reception of both the original packet and an acknowledgement on the same channel.

In this experiment, the data itself consisted of periodic reports on the quality of the communication paths, where a *path* represents all transmissions between a pair of wireless nodes. We allow for each node to have up to 8 neighbors and we communicate on all of the 16 channels. Each path is thus broken down into 16 *path-channels* representing the traffic on a particular channel for that path. A full description of all path-channels for a single node requires 128 entries of which we can fit 4 in a single packet. To report on all path-channels once per 15 minutes requires one packet every 28 seconds per node.

The *health* of each path-channel consists of the following data which is reported by every node and reset every 15 minutes:

- Channel number
- ID of neighbor
- Number of transmissions
- Number of transmit CCA fails
- Number of “No ACK” events
- Number of ACK CCA fails
- Number of receptions
- Mean RSSI for all receptions
- Mean LQI for all receptions

A successful transmission sequence results in the transmitting node incrementing the number of transmissions and the receiving node incrementing the number of receptions and averaging in the new RSSI and LQI measurement based on the ACK. A transmission without receiving an ACK results in incrementing the “No ACK” counter at the transmitter and could result in a few possible outcomes at the receiver. For the results that follow, we define the *stability* of a path-channel, as measured at the transmit end of the path, to be:

$$stability = 1 - \frac{\#NoACK}{\#Transmissions}$$

It is possible for the original packet to be received and queued by the receiver, but for the ACK to fail at the original transmitter. This event results in a duplicate packet and counts against stability in this measure.

Nodes closer to the gateway will have more transmit attempts in our architecture as all messages filter in their direction. We ensure that each node transmits at least once per minute to each of its two parents, so even the least busy nodes should record statistics for about 30 transmit attempts per 15 minute reporting period.

4. Overall Network Stability

The network had been operational for two weeks before the 97 hours of path-channel data were collected. Over the 4 days of the experiment, the same 91 paths remained the busiest in the network, and averaging over all of these paths gives a coarse estimate of overall network behavior. Figure 2 shows the time-averaged network stability for each channel. Based on this plot, no

channel appears significantly better or worse than any other when averaged over time and paths, and the network appears to function well on all frequencies. However, as appears in the following sections, channel properties can vary significantly in time and space.

Using CCA as a means of reducing energy costs by avoiding doomed transmissions does not succeed in this environment as shown in Figure 3. The most prevalent channel for CCA fails results in 0.13% of transmissions being aborted, far below the ~10% of packets that eventually fail on this same channel. The small number of CCA fails indicates that stability loss is likely not due to in-band interference from external energy sources.

Refining the mean stability analysis to path-level shows that there are some underperforming paths in the network. A histogram of these mean stabilities appears in Figure 4. During automated construction, the network management function does not explicitly choose high stability paths, but those with low stability do tend to fail during network formation. As such, there is self-selection of higher stability paths and a bias towards stability in functioning networks. When we break the paths down into path-channels, however, the tail of the distribution extends back to the origin as shown in Figure 5. Mistakenly choosing a low-stability path-channel in a single-frequency non-redundant network would result in data loss.

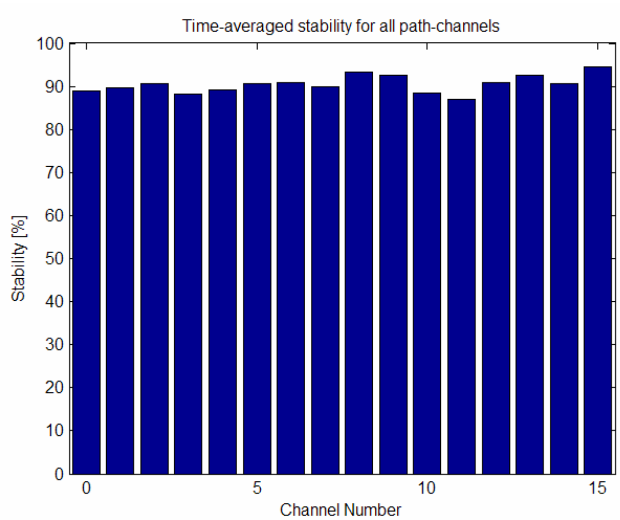

Figure 2. Stability as a function of channel averaged over all paths and time. A mean of 272550 transmit attempts occurred on each channel.

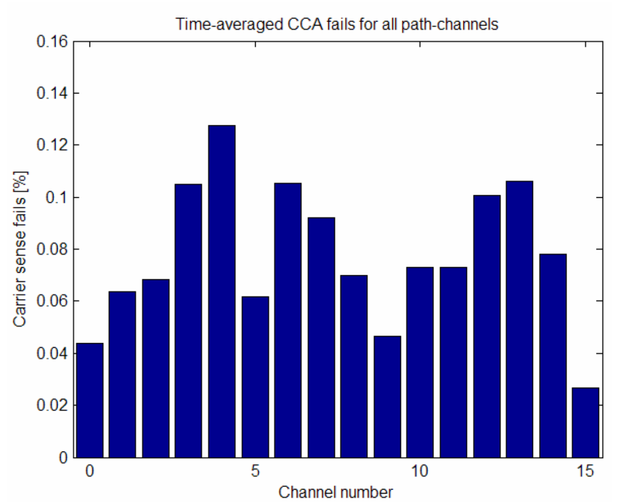

Figure 3. CCA fails as a function of channel averaged over all paths and time. The most contentious (channel 4) had 345 CCA fails in 270430 transmit attempts.

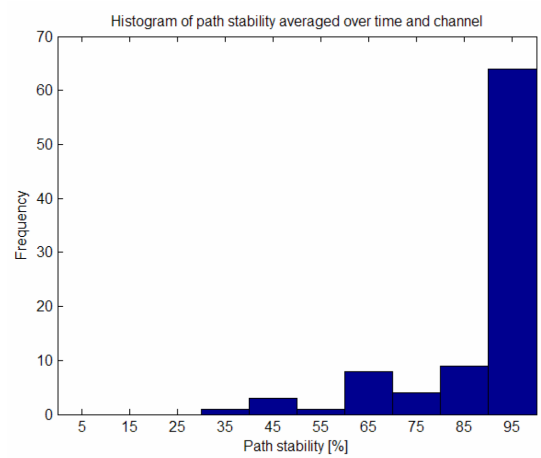

Figure 4. Histogram of all 91 used paths and stability.

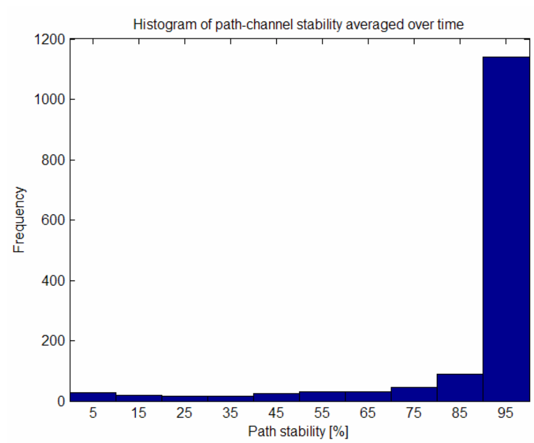

Figure 5. Histogram of all 1456 used path-channels. There are several path-channels below the lowest (35%) seen when averaged over all channels as in Figure 4.

5. Time-Averaged Single Path Analysis

By averaging over the time of the experiment, trends in general path-channel stability are apparent. The path between nodes 44 and 56 is summarized in Figure 6. This path had the highest traffic of all non-gateway paths. Stability varies from a low near 5% on channel 2 to a high above 95% on four other channels. RSSI data averaged over the same time period is plotted in Figure 7. Higher measured signal strength channels map to higher stability, but the inverse is not necessarily true as there is little difference in the signal strength of the poor- and mediocre-stability channels. The correlation of RSSI and stability suggests that signal energy differences, not interference, are responsible for the range of stability. This may be due to either multi-path effects or to the dependence in the RF opacity of obstacles to different frequencies. Lastly, the measured Link Quality Indicator (LQI) as provided directly by the CC2420 is averaged and plotted in Figure 8. While the scaling and offset of this metric are proprietary to the vendor, the general shape of the plot matches that of the path-channel stability suggesting that it is a valid metric for path-channel success. However, it exhibits the same time dependence that we will see in stability and RSSI, so it cannot be used to predict performance, only to measure it. Both RSSI and LQI are measured only on successful packets, so there is a bias towards higher readings for both.

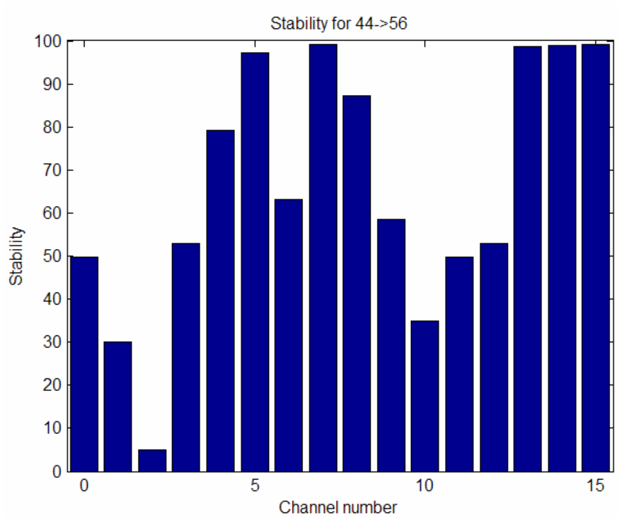

Figure 6. Stability of the 44→56 path shows definite frequency dependence. A mean of 2437 transmissions occurred on each channel.

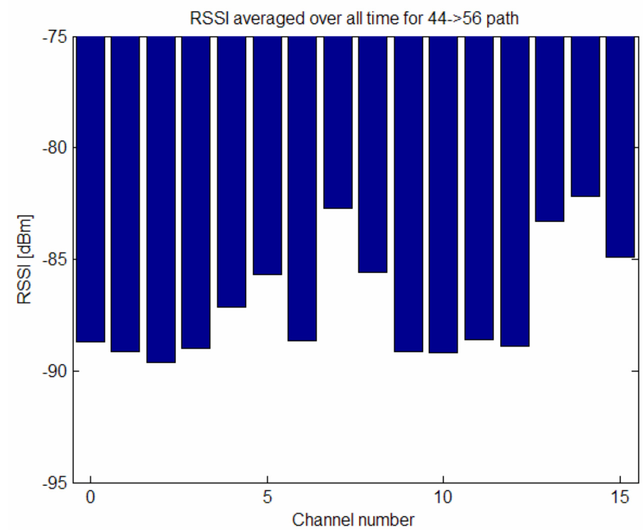

Figure 7. RSSI on the 44→56 path. The four highest RSSI channels correspond to those with the highest stability in Figure 6.

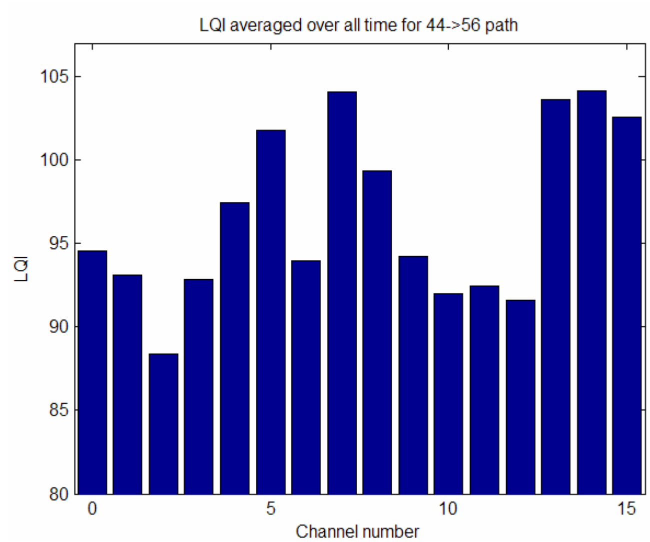

Figure 8. LQI on the 44→56 path. The general shape matches the stability plot of Figure 6.

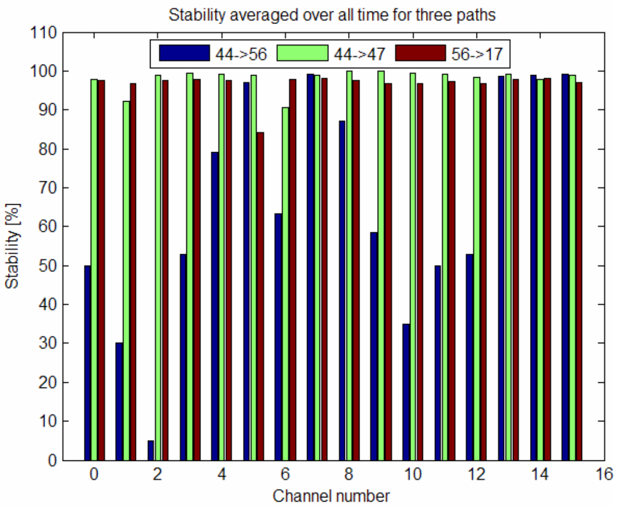

Figure 9. Three paths, including the one in Figure 6, have high and low stability on different channels.

The stability of three different paths, again averaged over time and broken down into path-channel statistics, is shown in Figure 9. The original 44→56 path was chosen along with one path involving each endpoint. Neither of the other paths exhibits low stability on channels 2 or 10 where the original performs the worst, and both have at least one low-stability channel where another path performed relatively well. This behavior illustrates that path-channel stability is not exclusively a function of a single endpoint; it is dependent on the physical nature of the path between the two nodes. Measurement of noise in the environment around a node is not sufficient to predict the frequency behavior of associated paths.

6. Time-Series Single-Path Analysis

Averaging over time, as done in the previous section, obscures the temporal behavior that varies across channels on a given path. The time-series behavior of two path-channels, along with the mean behavior for the path, is shown in Figure 10. Two medium-stability channels are chosen that exhibit different time-variance. While there is no pervasive trend in the mean stability of this path, there are long-term decreases in stability observed on the individual path-channels. In this example, there are periods of hours where channel 6 is at 100% while channel 11 is at 0% and vice versa.

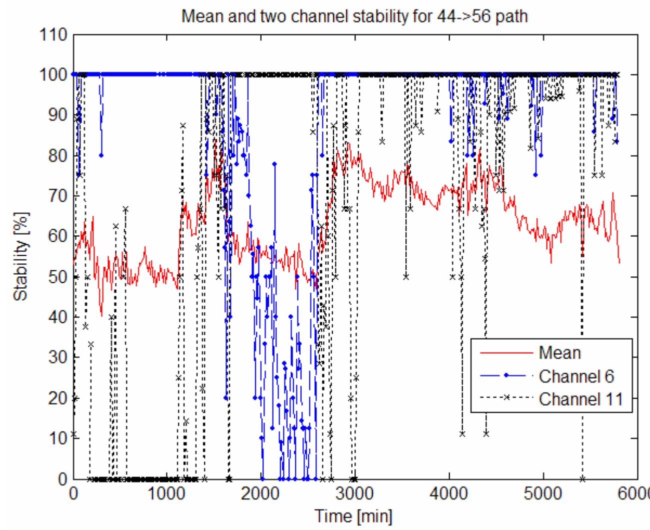

Figure 10. The average path stability for 44→56 does not capture the extreme time-variance of the component channels.

Plotting the measured RSSI over the same channels and time results in Figure 11. This plot shows that changes in channel stability are accompanied by changes in RSSI at roughly the same times and in the right direction, and illustrates how the two RSSI readings can trend in opposite directions. The cross-over points correspond roughly to the times when the stability levels switch from 0 to 100%. During 15 minute periods when no packets were successful, no RSSI reading is taken and the plot does not show a data point for this period. As such, the actual RSSI, if measurable, would have been lower than those indicated.

Path symmetry can be analyzed by comparing the RSSI as reported by either endpoint of the path. While different packet types are received by the two nodes, the same bit sequence preamble is used by the CC2420 to measure RSSI. The time sequence of RSSI averaged over all channels is shown in Figure 12. While both curves trend in the same direction, there is consistently a 3-4 dB difference between the two. This asymmetry is likely due to output power differences among devices. Correlation between RSSI measured at the endpoints on a single channel, not shown here, is even tighter but still exhibits the 3-4 dB difference. This correlation suggests that the channel properties are unchanged on the time scale between the original packet and the ACK, on the order of 10 ms.

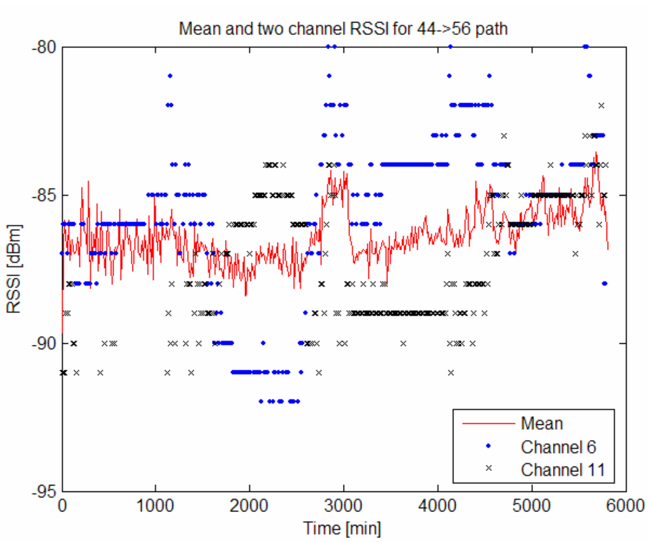

Figure 11. The RSSI measurements show similar breakpoints to Figure 10. RSSI is measured at node 44 based on the signal strength of received ACKs. The absence of data, particularly for channel 11, is during periods of 0% stability on this path-channel.

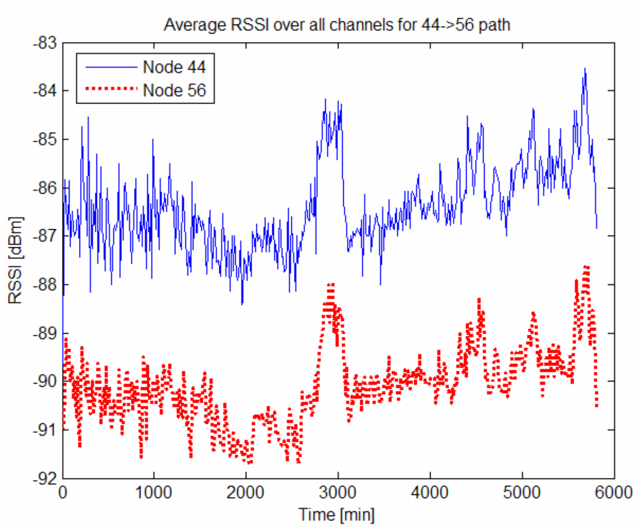

Figure 12. RSSI averaged over all channels in 15 minute intervals for both endpoints of a path. Node 56 measures the RSSI on received packets while node 44 uses the signal strength of received ACKs.

7. Conclusions and Future Work

This paper is intended mainly to show some of the properties of the data collected in our experiment, not necessarily to draw conclusions about the physics behind the wireless propagation. The full data set of 91 paths can be obtained by contacting the authors. It is precisely because behavior of path-channels escapes simple modeling that we felt the need to gather a real set of data from a physical deployment in a challenging environment.

Though the majority of paths in the test network had high average stability, reliability of sensor networks must be maintained even during periods of stress. Stability in the deployed wireless sensor network varies wildly over time, space, and frequency in ways that are difficult to capture with theoretical models. RSSI is a valid predictor of path-channel stability, but RSSI itself varies over time. On short time scales of milliseconds, RSSI remains constant, but it changes significantly (more than 10 dB) over minutes. Both RSSI and stability can decrease precipitously on certain channels at the same time that they rise on others. There is no site survey that can be done to adequately predict the behavior of a network installed at that location, and there is even less hope of a theoretical model capturing the complexity of the variability of these wireless channels.

In the face of these challenges, our approach remains to employ path and frequency diversity in all data traffic. By hopping over all channels equally, we can guarantee that we meet, on average, the mean performance of the path which varies considerably less than its components. CCA, at least in the CC2420 hardware, cannot be used on its own to selectively broadcast in an efficient manner. By encouraging each node to have two parents, the resulting mesh is less susceptible to unpredictable effects on paths. In the 25 days of operation of this network to date (during which the 4 days of logging occurred as a part), only 17 packets were lost out of a total of 3.574 million generated. This represents a delivery rate of 99.9995%.

8. References

[1] K. Whitehouse, C. Karlof, D. Culler. "A Practical Evaluation of Radio Signal Strength for Ranging-based Localization". ACM MC2R, Special Issue on Localization Technologies and Algorithms. 2007.

[2] K. Sohrabi, B. Manriquez, and G. Pottie, “Near-ground wideband channel measurements”. Proceedings of the 49th Vehicular Technology Conference, Houston, May 1999.

[3] D. Sexton, M. Mahony, M. Lapinski and J. Werb, “Radio Channel Quality in Industrial Wireless Sensor Networks”, Proceedings of Sicon 2005, Houston, TX, February 2005.

[4] The full 802.15.4/ZigBee specification can be obtained for non-commercial purposes at zigbee.org.

[5] TI Chipcon CC2420 Datasheet

[6] L. Doherty and D.A. Teasdale, “Towards 100% Reliability in Wireless Monitoring Networks”, Proceedings of PE-WASUN 2006, Torremolinos, Spain, October 2006.

[7] A technical description of TSMP is available at: http://www.dustnetworks.com/docs/TSMP_Whitepaper.pdf