Structure Health Monitoring at MRT Construction Sites Using Wireless Sensor Networks
Link Measurement at Pasir Panjang Station

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Abstract

In this project, we study the radio behavior of currently-available sensor platforms at MRT construction sites. With the deployed 22-node testbed at Pasir Panjang station, consisting of 11 Mica2 and 11 MicaZ nodes, we conducted detailed measurement of link qualities between sensor nodes. The results we obtained show that Mica2 performs better than MicaZ, in terms of radio penetration, which is most likely due to Mica2's lower radio frequency ($433MHz$) than MicaZ ($2.4GHz$). But we also observed that MicaZ also has very good connectivity in relatively open area. Since MicaZ has much higher radio bandwidth and energy efficiency in bulk data transmission, we believe that it may be beneficial to have both radios on board and dynamically select the one that will optimize network performance.

1 Introduction

Structure Health Monitoring (SHM) plays a crucial role in assessing the integral safety of structures like buildings and bridges, both during the process of and after construction. While most such existing monitoring implementations employ wired data acquisition system to collect structural health data for analysis, a wireless monitoring solution will provide benefits such as low installation and maintenance cost, flexibility of deployment, and more safety. Therefore, since the emergence of Wireless Sensor Networks (WSN), structure health monitoring has attracted a lot of research foci. Some research groups have tried deploying sensor nodes at places like Golden Bridge and coal mines.

To improve the public transportation system, Singapore government has planed to expand its MRT system by building Circle Line and Downtown Line, consisting of 62 stations in total. Since it is important to be able to monitor the infrastructure health status during the construction process, a wired monitoring system has been installed at every MRT construction site. However, due to the shortcomings of aforementioned wired system, it is worthwhile and beneficial to upgrade the monitoring system by making use of currently-available WSN technology. As per our knowledge, we are one of the very few to deploy WSN at MRT construction sites.

1.1 Project Goals

In this project, we aim to develop and deploy a WSN-based monitoring system for SHM at MRT construction sites. As building such a system is a complex problem with many unknowns, we plan to carry out our research in the following three stages.

Stage 1 Study the feasibility of wireless communication at MRT sites by deploying a sample sensor network and collecting detailed link measurement data for analysis.

Stage 2 Design energy efficient and robust routing algorithm for sensing data collection.

Stage 3 Build and deploy industrial prototype nodes with interface to the existing monitoring sensors.

1.2 Our Contributions

Throughout Stage 1 of the project, we have achieved the following:

- Built a working data collection system for outdoor WSN deployment.
- Verified important factors that affect wireless communication in harsh environment.
- Measured battery lifetime for sensor nodes and validated the energy consumption model.

1.3 Report Organization

This report presents the link measurement project and results we obtained thus far. The rest of the report is organized as follows. Section 2 describes the overall system architecture and setup for link measurement. Section 3 shares the experience of two deployments at Pasir Panjang MRT station. Section 4 presents the plot for link information and sensing data. Section 5 concludes the report and discusses some possible next steps.

2 System Architecture and Setup

In this section, we first explain why we think of deploying sensor nodes with different radio frequency. Then we present the whole picture of the link measurement system, which consists of three components: sensor nodes, base station nodes and gateway node. Finally, we show how to configure each of them to measure the link qualities among nodes.

2.1 Why two types of sensor nodes?

Figure 1: Construction site at Pasir Panjang MRT station

To conduct link measurement, we chose to install sensor nodes at Pasir Panjang station, which is currently under construction. As shown in Figure 1, metal beams are almost everywhere, resulting harsh environment for radio propagation and large attenuation factors. Therefore, before actual deployment, we expected high-frequency radio to have much shorter transmission range, compared to low-frequency radio. Taking this into consideration and given the two types of sensor nodes we currently have, we plan to try both nodes and get a clearer picture about how transmission frequency affects the radio propagation and which radio performs better at such harsh environment. Table 1 shows the radio characteristics for the two types of sensor nodes: Mica2 and MicaZ.

Sensor Node	Radio Frequency	Bandwidth	Tx Range (Outdoor, LOS)
Mica2	433MHz	19.2kbps	300m
MicaZ	2.4GHz	250kbps	75-100m

Table 1: Radio characteristics for Mica2 and MicaZ

2.2 Equipment List

- Sensor nodes: 11 Mica2 and 11 MicaZ nodes attached with weather sensor boards `MTS400`
- Base station nodes: 2 stargates with Mica2/MicaZ attached and with WiFi capability
- Gateway node: 1 desktop PC with WiFi capability and Internet access

2.3 System Layout

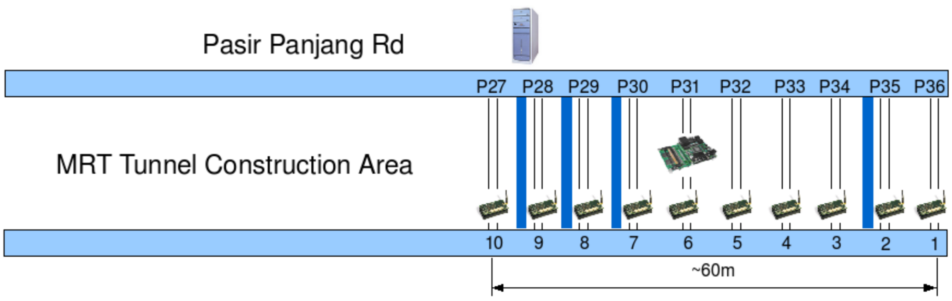


Figure 2: System layout at Pasir Panjang station

Figure 2 shows the layout of the whole link measurement system, which consists of 10 pairs of nodes and covers 10 metal beams from beam P27 to P36. The average distance between two neighboring beams is about 7 meters, resulting in a total coverage of about 60 meters. Base station nodes (Figure 4) are placed on beam P31, with 1 car battery and 2 stargates inside. Gateway node (Figure 5) is placed along Pasir Panjang Road and next to beam P29. The blue-colored beams are the ones that are 30cm wide and 50cm above the normal ones. We will see the effect of such heavy beams on radio propagation in Section 4.

The system works in a centralized manner with base station nodes as central controller. In general, link measurement is conducted in rounds with a period of about 12 minutes, among which each node will send/receive packets for 47 seconds and then sleep for 11 minutes.

In the beginning of each measurement round, base station nodes first broadcast the `start` command, specifying the sender node, transmit power levels, data packet size and link measurement period. In each measurement round, there is only one sender node and the rest are receiver nodes. While the sender is transmitting data packets, receiver nodes just count the number of packets they receive.

At end of one measurement round, all nodes will send back their counts to base station, who will request for retransmission in the presence of packet loss. After collecting all the measurement results, base station nodes will broadcast the `sleep` command, specifying the sleep interval. Upon receiving `sleep` command, a sensor node will first broadcast `sleep` command and then turn off its radio and put itself into sleep mode. We add this flooding feature to make sure every node will receive the texttsleep command with high probability. For base station nodes, they have to turn on the WiFi card, upload the compressed result data to gateway pc and turn off the WiFi, before they put themselves into sleep mode. Gateway pc regularly checks and uploads data to the server at School of Computing, NUS.

2.4 Configuration for Sensor Nodes

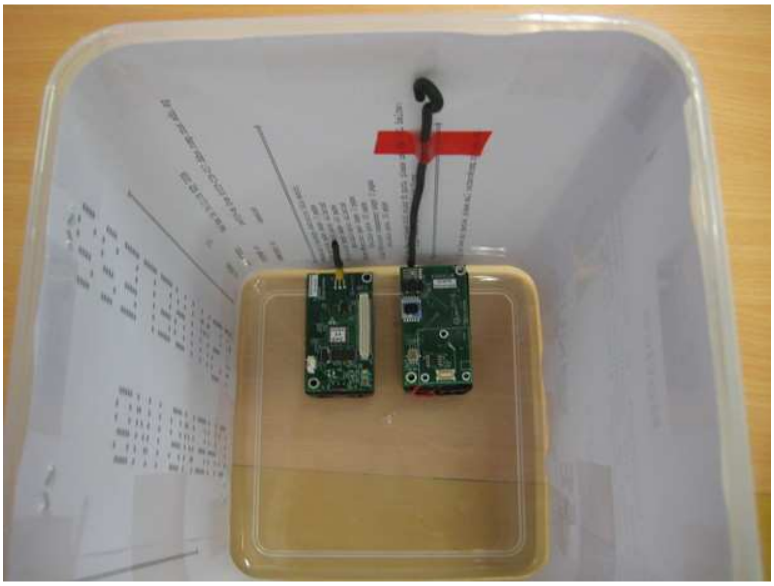


Figure 3: Sensor nodes inside a box

One pair of sensor nodes consist of one Mica2 and one MicaZ, as shown in Figure 3. We put them inside one box, in order to compare link quality for the two radios in a relatively fair way. Since we expect the link measurement to run for a longer time, each node is instructed to sleep and wake up periodically. In our setup, due to the radio bandwidth difference, Mica2 nodes will measure link quality for 47 seconds and then sleep for 11 minutes, resulting a duty-cycle of 6.65%, while MicaZ for 19 seconds and 11.5 minutes respectively, with a duty-cycle of 2.69%. Both Mica2 and MicaZ also collect weather board sensing data every 10 minutes and send them to base station nodes together with the link measurement data. So in one link measurement round, a Mica2 node will send about $16.5KB$ data, if it is the sender node, and receive about $16.5KB$ data, if it is a receiver node. MicaZ nodes send/receive about the same amount of data as Mica2.

2.5 Configuration for Base Station Nodes

Figure 4: Base station nodes inside a box

As central controller, base station nodes (stargate with Mica2/MicaZ attached) run an embedded version of Linux and are powered by a car battery shown in Figure 4. Periodically, stargate will start the link measurement, upload results to the gateway node, and then put itself to sleep mode. From our experience, the $35Ah$ car battery we used can only last for 5.5 days, which becomes the bottleneck for our system. To avoid the recharging issues, we can either use AC power, solar panels, or two car batteries for swap.

2.6 Configuration for Gateway PC

Figure 5: Gateway pc inside a box

Gateway pc, shown in Figure 5, provides the Internet access via an M1 HSDPA USB modem and regularly uploads measurement results to our school's server. It also provides the time synchronization service for the stargate nodes. The current issue is about power failure. The gateway pc will not power up by itself after power failure. We can solve this problem by replacing with an enhanced pc and using car battery as temporary backup power supply.

3 Site Deployments

In this section, we share our experience of two deployments for link measurement. The first one was for temporary use, but the measurement results gave us useful hints for node placement. The second one targeted at relatively long-term link measurement. And up to now, we have collected 15 days' measurement results, due to the car battery bottleneck.

3.1 First Deployment

We first went down in late January and collected measurement results for three afternoons. In this deployment, we directly placed a node pair on top of the beams, as shown in Figure 6. The results we obtained

Figure 6: Node placement in first deployment

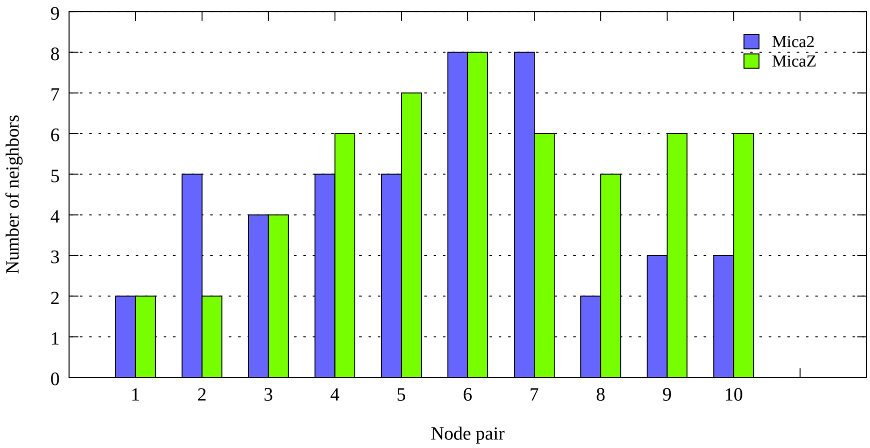


Figure 7: Number of neighbors for each node in first deployment

were somehow unexpected. Figure 7 plots the number of neighbors a Mica2/MicaZ node has, showing that in most cases, Mica2 has same number o for fewer neighbors than MicaZ. On average, a Mica2 node has 4.5 neighbors while MicaZ has 5.2. However, Mica2 has a much lower transmission frequency and therefore should have better propagation penetration.

In our lab, we repeated the same measurement by placing nodes directly on floors. And we got similar results as at Pasir Panjang station. After searching, we doubted that this might be due to the ground effect. Then we put the nodes on chairs, with about $0.5m$ above the floor, and measured the link quality. We found that both Mica2 and MicaZ have about 9 neighbors, showing a very good connectivity.

3.2 Second Deployment

Figure 8: Node placement change in second deployment

Encouraged by the results in lab, we went down for the second deployment. In Figure 8, the yellow circle shows the new place we chose for deployment, which is about $1.2m$ above the beams. With these changes, we conducted link measurement and got 15 days' data, which we will present in Secton 4.

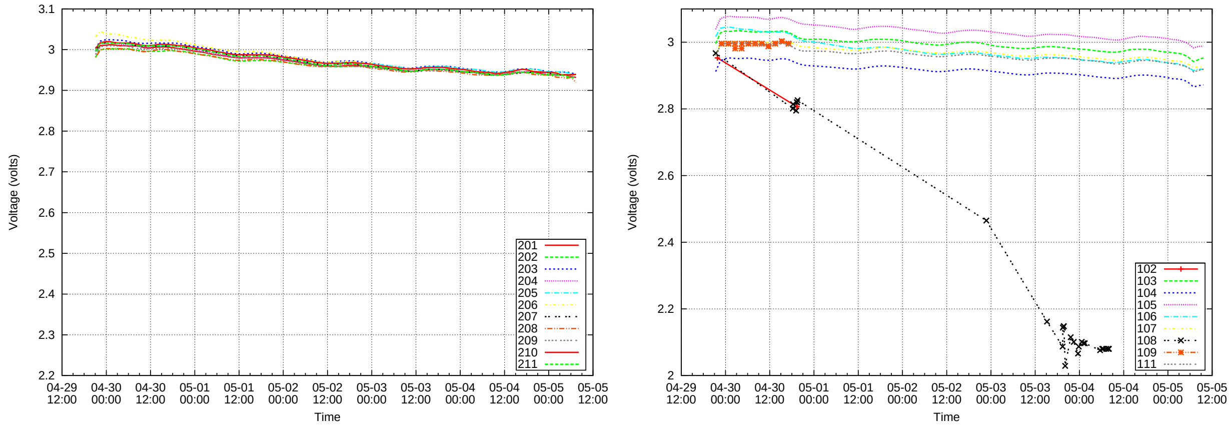
4 Measurement Results

In this section, we present both link measurement and sensing data collected from the second deployment. As the three data sets are similar, here we only select the first set (from Apr 29 to May 5) for plotting.

4.1 Lifetime Estimation for Sensor Nodes

Network lifetime is crucial for most outdoor deployment, since it is not always easy or practical to change node batteries. To be able to predict network lifetime, we did node lifetime estimation based on the voltage data we collected from each node and a linear energy dissipation model. The model assumes that for periodic sensing applications, the energy consumption for sensor nodes is proportional to the number of sensing cycles.

Figure 9(a) shows the voltage drop for 11 Mica2 nodes: 201–211, over 5 days and 10 hours. Therefore,



(a) Mica2 nodes

(b) MicaZ nodes

Figure 9: Voltage drop for sensor nodes

the average voltage drop per node per day is:

$$\frac{88.9mV}{5days10hours} = 16.5mV/day$$

Assuming an initial voltage level of $3.2V$ and the minimum working voltage level of $2.2V$, we can calculate the estimated lifetime for Mica2 nodes:

$$\frac{3.2V - 2.2V}{16.5mV/day} = 60.6days$$

In our case, the average initial voltage level for the 11 Mica2 nodes is $3.015V$, resulting an estimated lifetime of 49.4 days.

Similarly, for MicaZ nodes, the average voltage drop per node per day is $21.5mV/day$. The estimated lifetime with $3.2V$ initial voltage level is 46.5 days. With average initial voltage of $3.023V$, the lifetime is 38.3 days.

4.2 Link Quality Data

Since the radios in Mica2 and MicaZ are different, especially the radio energy consumption, we try to make comparisons as fair as possible, by using the metric of current draw. Table 2 shows the current draw of Mica2 and MicaZ radios with different transmit power levels.

Mica2		MicaZ	
Transmit power (dBm)	Current draw (mA)	Transmit power (dBm)	Current draw (mA)
8	20.0	0	17.4
7	16.8	-1	16.5
5	14.8	-3	15.2
4	13.8	-5	13.9
2	12.8	-7	12.5
1	11.8	-10	11.2
-2	9.7	-15	9.9

Table 2: Current draw of different transmit power levels for Mica2 and MicaZ radios

Figure 10 shows the connectivity information, i.e. number of neighbors Mica2 and MicaZ have, for three groups of transmit power levels: Mica2 $7dBm$ vs. MicaZ $0dBm$, Mica2 $4dBm$ vs. MicaZ $-5dBm$, Mica2 $-2dBm$ vs. MicaZ $-15dBm$, representing high, medium and low powers respectively. We can see that in all three groups, Mica2 nodes have more neighbors than corresponding MicaZ nodes.

Figure 11 shows the temporal behavior of wireless links, by plotting the number of neighbors a node has over time. We can see that for node 201 and 209, although the number of neighbors fluctuated over time, the difference is relatively small, 3 for 201 and 2 for 209. However, for node 202, the difference is quite prominent, since sometimes it was even disconnected from the whole network.

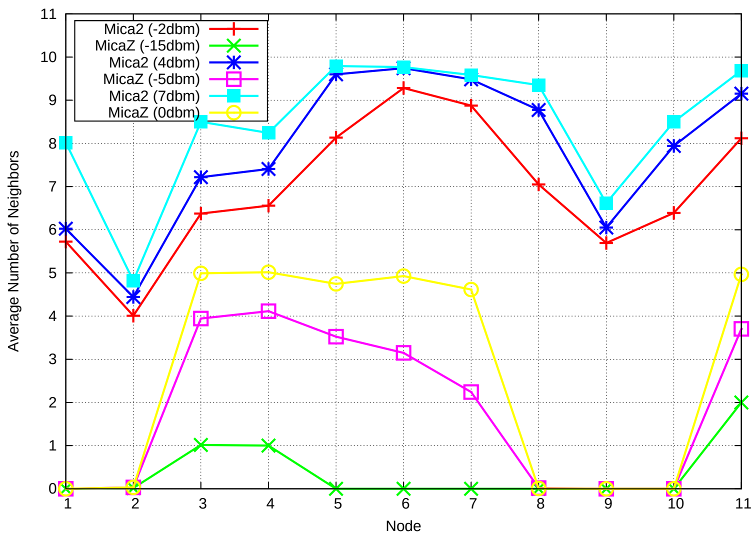


Figure 10: Number of neighbors for Mica2 and MicaZ

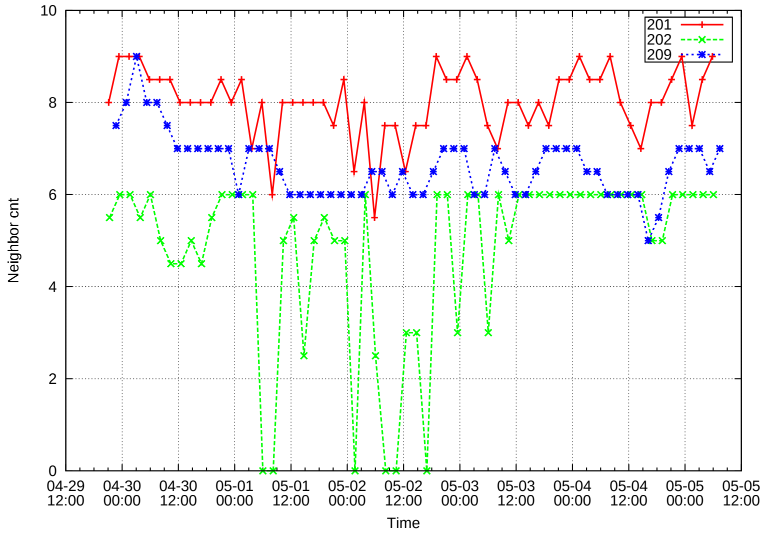


Figure 11: Temporal link behavior for some Mica2 nodes

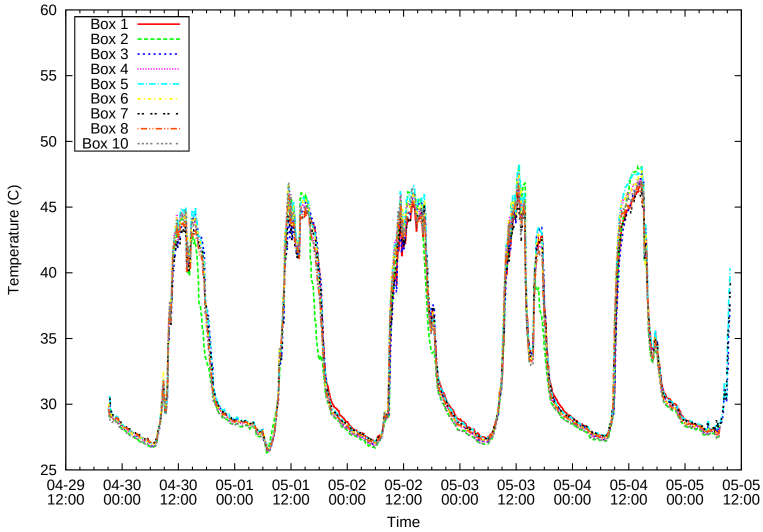


Figure 12: Temperature data for each node box

4.3 Sensing Data

Although we have collected sensing data such as temperature, relative humidity and acceleration. Here due to space constraint, we only present temperature data for illustration. Figure 12 plots the temperature inside the node box over 5 days. We can see that the temperature can reach as high as more than $45°$C at noon and as low as about $26°$C in the morning.

5 Conclusion and Next Steps

As the first step of this monitoring project, we conducted link measurement for two types of sensor nodes: Mica2 and MicaZ. The results we obtained show that in the harsh environment like MRT construction sites, Mica2 has better radio propagation penetration, thus can reach more nodes than MicaZ. But we also observed that in relatively open area, MicaZ has very good connectivity. Since MicaZ has higher energy efficiency in data transmission and much larger radio bandwidth, we believe that it may be beneficial to have both radios on board and dynamically select which one to use.

For the following steps, we think that the followings can be done: 1). select Mica2 as the target node platform for data collection and design efficient routing algorithm with duty-cycling; 2). build industrial prototype nodes with interfaces to the existing monitoring sensors and study the overall energy consumption.

6 Acknowledgments

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