Performance Analysis of Wireless Devices for a Campus-wide IoT Network

Nihesh Rathod†, Pratik Jain¶, Renu Subramanian†, Siddhesh Yawalkar†, Mallikarjun Sunkenapally¶, Bharadwaj Amrutur† and Rajesh Sundaresan†.
†Department of Electrical Communication Engineering, ¶Department of Electronic Systems Engineering
Indian Institute of Science, Bangalore 560012, India

***Abstract*—To select an appropriate technology for the deployment of an Internet-of-Things (IoT) network inside the Indian Institute of Science (IISc) campus, we first compare available wireless technologies based on their data sheets. After selecting two of the best available sub-GHz devices, we characterize them by performing controlled lab experiments. Next we test these sub-GHz modules in different real world environments such as open ground, straight road, moderately and densely wooded area, inside a concrete building and on building roof-tops. We then compare their performances for characterization of the wireless channels in different environments. In the end, we propose a sensor and network plan towards monitoring water resources inside the IISc campus.**

***Index Terms*—Internet of Things, Mote and antenna characterization, Channel characterization, Sub-GHz.**

I. Introduction

Unlike wired devices, performances of wireless devices in practical settings can vary significantly from those obtained either via simulations based on theoretical propagation models or in lab settings. Field testing is therefore crucial. In this paper, we summarize field-testing data from two sub-GHz platforms. The experiments were done to identify a suitable platform for a campus-wide Internet-of-Things (IoT) network. In the next three paragraphs, we describe aspects of our methodology.

A key performance indicator in a large area sensor network deployment is power consumption. Significant amount of power is consumed for sensing, network maintenance, data transmission and reception. Data sheet based comparison of different technologies gives some insight into power requirements. Section II-A describes our procedure for comparing existing technologies based on their energy requirement with the help of data sheets. The comparisons themselves are in section II-B.

Sensitivity may vary across different hardware radios even though their specifications are same. Hence, prior to conducting field experiments, it is essential to ensure that the modules and antennas are working as per specifications, or to identify a suitable calibration. Section III-A describes the experimental procedure we used for mote characterization in a controlled environment. We present our findings in section III-B.

Characterization of the radio channel is as important as mote/device characterization for an efficient system deployment. This is not only a feature of the device, but also one that is heavily dependent on the environment. So, it is necessary to conduct these experiments across different terrains such as open grounds, straight roads, moderately and densely wooded areas, inside concrete buildings, and across building rooftops. Section IV-A explains our procedure for conducting field experiments. We present our comparisons in section IV-B.

Armed with the above observations and results from our field experiments, we propose in section V a viable sensor network deployment plan for monitoring water levels of ground level reservoirs (GLR) and overhead tanks (OHT) inside the Indian Institute of Science (IISc) campus. This network is going to serve as a test bed for campus-wide IoT deployment which will enable us to deploy a sensor on-the-go without worrying about repeater positions.

II. Data sheet comparison

In this section, we present some key parameters extracted from the data sheets of the following devices.

1) Sub-GHz devices:
- Texas Instruments CC1200-DK [1].
- Semtech LoRa iM880A [2].
- Telit LE51-868-S [3].

2) GPRS/GSM modules:
- CEL 09533 [4].
- LEON-G1 [5].
- SARA-G3 [6].

We compare their energy consumption based on a certain activity profile, and then present our baseline conclusions.

Zigbee and WiFi are short range devices. IISc campus is large for such devices (2 km x 2 km) and is mainly wooded. So, long range devices like GSM/sub-GHz will be a better option for our deployment.

A. Procedure

For achieving homogeneity across different devices, transmission power for each device was set at 14 dBm. GSM standard requires mobile devices to transmit at much higher power than 14 dBm, of the order of 32 dBm, requiring much higher transmission current. So, for validation of this calculation we scaled down the transmission current of GSM module by a factor of 64 (which comes from (32-14) dBm). Regulated 3 V power supply was used for the experiment.

We calculated energy requirements in terms of Joules at 3 V because of the ease of calculation of the running time of devices operating on battery supply.

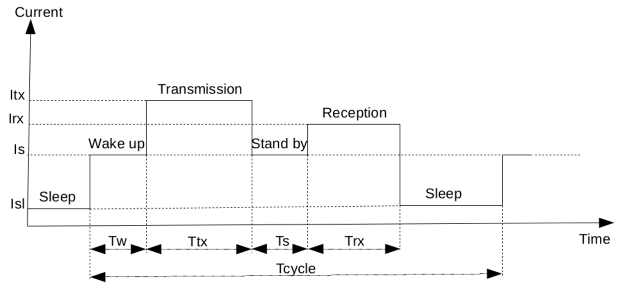

Fig. 1: Operation Cycle.

Tables I-II show current values required for different modes of operation such as transmission, reception, receiver standby and sleep for the different devices.

TABLE I: Current values for Sub-GHz transceivers.

	iM880A	CC1200-DK	LE51-868 S
Peak Tx current	42 mA	46 mA	55 mA
Rx current	11.2 mA	19 mA	32 mA
Rx standby current	1.5 mA	0.5 mA	2 mA
Sleep current	0.1 μA	0.12 μA	1 μA

TABLE II: Current values for GPRS/GSM transceivers.

	CEL 09533	LEON-G1	SARA-G3
Tx current	6.25 mA	6.625 mA	5.5 mA
Rx current	100 mA	10 mA	18 mA
Rx standby current	13 mA	1.6 mA	4.7 mA
Sleep current	100 μA	90 μA	40 μA

Power consumption depends upon the various operation states of the devices. Moreover, energy spent by device over an operational cycle depends on how much time the device spends in each state. As these values are different for different devices, it is essential to consider an appropriate test scenario for comparing them in terms of energy requirement.

Fig. 1 describes our assumption on the typical operating cycle of the device for calculating energy consumption. T_{cycle} is the time period for one cycle of operation which is assumed to have a period of 60 seconds. T_w is the wake up time that varies depending upon the device, which is directly taken from its data sheet. T_{tx} is the time taken for transmission of a single packet of size 20 Bytes, out of which 16 Bytes carry data, including packet header and 4 Bytes of checksum. The device waits for data reception for T_s time. T_{rx} is the time taken for receiving 2 identical packets of 20 Bytes.

Equation (1) gives us the power consumption for one operation cycle (at 3 V).

$$Q = \int_{T_w+T_s} I_s dt + \int_{T_{tx}} I_{tx} dt + \int_{T_{rx}} I_{rx} dt + \int_{T_{sleep}} I_{sl} dt. \quad (1)$$

B. Comparisons

Tables III-IV show energy consumption values calculated from equation (1) for different devices.

TABLE III: Energy values for sub-GHz transceivers.

	iM880A	CC1200-DK	LE51-868 S
T_x	24 ms	24ms	24ms
R_x	48 ms	48 ms	48 ms
$T_s + T_w$	10 ms	10 ms	10 ms
T_{sleep}	59918 ms	59918 ms	59918 ms
T_x energy	1056 μC	1104 μC	1320 μC
R_x energy	537 μC	912 μC	1536 μC
Standby energy	15 μC	5 μC	20 μC
Sleep energy	6 μC	7.2 μC	60 μC
Energy per cycle	4.84 mJ	6.08 mJ	8.83 mJ

TABLE IV: Energy values for GSM/GPRS modules.

	CEL 9533	LEON-G1	SARA-G3
T_x	24 ms	24 ms	24 ms
R_x	48 ms	48 ms	48 ms
$T_s + T_w$	10 ms	10 ms	10 ms
T_{sleep}	59918 ms	59918 ms	59918 ms
T_x energy	150 μC	159 μC	132 μC
R_x energy	4800 μC	480 μC	864 μC
Standby energy	130 μC	16 μC	46 μC
Sleep energy	6 mC	5.4 mC	2.4 mC
Energy per cycle	33.24 mJ	18.14 mJ	10 mJ

The above calculations show that even the highest energy consuming sub-GHz device (Telit LE51-868-S) performs better than the lowest energy consuming GSM module (SARA-G3). GSM modules require at least about 1.15 times more energy than sub-GHz modules. On an average, GSM modules require 3.15 times more power than sub-GHz devices. Moreover, among the three sub-GHz devices, Semtech LoRa iM880A is more energy efficient than TI CC1200-DK and Telit LE51-868-S.

We chose two of the least power consuming sub-GHz devices for our experiments namely Semtech LoRa iM880A and TI CC1200-DK. Moreover, development kits for these two devices are easily available with pre-loaded software stack and GUI interface.

III. Mote Characterization

Prior to conducting field experiments, we measured antenna sensitivity and actual transmitted power for CC1200-DK and LoRa iM880A devices using a spectrum analyzer. This section describes the experiment, observations, and baseline conclusions.

A. Procedure

We first performed an open end calibration of the spectrum analyzer. This was followed by load calibration of the module for the spectrum analyzer. The above procedure ensured that the spectrum analyzer is calibrated for compensating cable loss and impedance mismatch. We then transmitted at three different power levels, 5 dBm, 10 dBm, and 14 dBm, and measured the transmitted power on the spectrum analyzer. The above procedure was followed for both modules. Agilent Technologies N9912A spectrum analyzer was used for these experiments.

To measure antenna sensitivity, we kept one module on continuous transmission mode at 14 dBm and measured the power level on the spectrum analyzer using different antennas of the same model. The antenna model which showed minimum variation in sensitivity was selected for field experiments.

The above specified procedures ensured that the field experiments would give accurate readings that are based solely on module characteristics.

B. Results

Table V shows the configured and actual transmission powers (as reported by the spectrum analyzer); Δ_1 and Δ_2 are the differences between actual powers and configured powers for the CC1200-DK and LoRa iM880A devices, respectively.

TABLE V: Configured and actual power levels.

Configured power	5 dBm	10 dBm	14 dBm
CC1200-DK	4.46 dBm	10.02 dBm	14.67 dBm
Δ_1	-0.54 dBm	0.02 dBm	0.67 dBm
iM880A	5.36 dBm	10.49 dBm	14.41 dBm
Δ_2	0.36 dBm	0.49 dBm	0.41 dBm

Transmission powers for both the CC1200-DK and LoRa iM880A were different from the set values. iM880A transmitted at 0.3 - 0.5 dBm higher than the configured power. The CC1200-DK device's transmitted power was 0.54 dBm lower than the nominally set value of 5 dBm. It was nearly 10 dBm for the 10 dBm setting and was 0.67 dB higher at the 14 dBm setting.

IV. Field Experiments

In this section, we present two performance indicators – Received Signal Strength Indicator (RSSI) and Packet Error Rate (PER) – obtained through field experiments in different environments on the two sub-GHz devices : 1) CC1200-DK, and 2) LoRa iM880A. Comparisons follow.

A. Procedure

For fairness of comparison of the results across all environments and across both wireless modules, on-air packet size was kept the same (25 Bytes). On-air time was also kept the same at 46.4 ms. For LoRa iM880A, physical payload was 15 Bytes with 8 Bytes of header (RF control field, Destination group and device address, source group and device address, radio stack fields) and 7 Bytes of data. Additionally, iM880A firmware adds 10 Bytes header (Preamble symbols, firmware header symbols and CRC). For CC1200, data was 16 Bytes. Additionally, CC1200 radio adds 9 Bytes (Preamble symbols, Sync word and CRC). So 25 Bytes of iM880A on-air packet contains 7 Bytes of data while 25 Bytes of CC1200 on-air packet contains 16 Bytes of data. Fig. 2-4 show the on-air packet format for the radios. We presume now that these header inefficiencies can be handled by tweaking the protocol at a later stage, so as to proceed with the assumption that on-air packet size to information bits ratio can be made as small as possible and the same across both platforms.

Number of packets transmitted was set to 1500 in cases a), d), e) and 1000 in cases b), c), f) in section IV-A. The transmitter and receiver were kept on a table of height 48.26 cm.

Preamble Symbols 7 Bytes	Header Symbols 1 Bytes	Physical Payload 15 Bytes	CRC 2 Bytes

Fig. 2: On-air packet structure of iM880A.

Radio Ctrl Field 1 Byte	Dest. Group Addr. 1 Byte	Dest. Device Addr. 2 Bytes	Source Group Addr. 1 Byte	Source Device Addr. 2 Bytes	Radio Stack Fields 1 Byte	Data 7 Bytes

Fig. 3: iM880A physical payload field.

Preamble 3 Bytes	Sync word 4 Bytes	Data 16 Bytes	CRC 2 Bytes

Fig. 4: On-air packet structure of CC1200.

The experimental setup had the following specifications:

1) LoRa iM880A
   - Carrier frequency: 869.5 MHz
   - Modulation scheme: LoRa proprietary modulation
   - Bandwidth: 125 KHz
   - Bit rate : 5.4 kbps
   - Spreading factor : 7
   - Coding rate : 4/5
2) CC1200-DK
   - Carrier frequency: 868 MHz
   - Modulation scheme: 2-FSK
   - Bandwidth: 128 KHz
   - Bit rate : 4.6 kbps

In each case, we measured RSSI, Bit Error Rate (BER), number of packets received correctly, and the PER. For iM880A, the above experiment was conducted for three different power levels, 5 dBm, 10 dBm and 14 dBm. To match the actual transmitted powers of both the radios, power levels for CC1200 were set to 6 dBm, 11 dBm and 14 dBm to get the closest match; see Table VI for actual transmitted powers and the energy/bit based on measured power levels by the spectrum analyzer.

TABLE VI: Energy / bit for CC1200-DK and iM880A.

Configured power	6 dBm	11dBm	14dBm
Measured power on spectrum analyzer	5.175 dBm	10.9 dBm	14.67 dBm
CC1200-DK	0.7638 μJ	2.8542 μJ	6.7996 μJ

Configured power	5 dBm	10dBm	14dBm
Measured power on spectrum analyzer	5.24 dBm	10.49 dBm	14.41 dBm
iM880A	0.7753 μJ	2.5970 μJ	6.4045 μJ

Experiments were conducted in the following locations inside the IISc campus. See Fig. 5. Locations for cases c), d) and f) were marked using Google Maps and a GPS location service. In locations marked with *, a newer W5017 Pulse Antenna was used, while other locations, a simple dipole antenna was used.

a) Open area:* Location A: Cricket ground, Gymkhana, IISc. Distances between transmitter and receiver: 50 m, 100 m, 150 m, 200 m, and 250 m.

b) Straight road: Location B: Gulmohar Marg, IISc. Distances between transmitter and receiver: 250 m, 500 m, 750 m, and 1 km.

c) Moderately wooded area: Location C: Rectangular wooded area enclosed by Gulmohar, Tala, Madhura, and Amra Margs in IISc. Distances between transmitter and receiver: 50 m, 100 m, 150 m, 200 m, and 250 m.

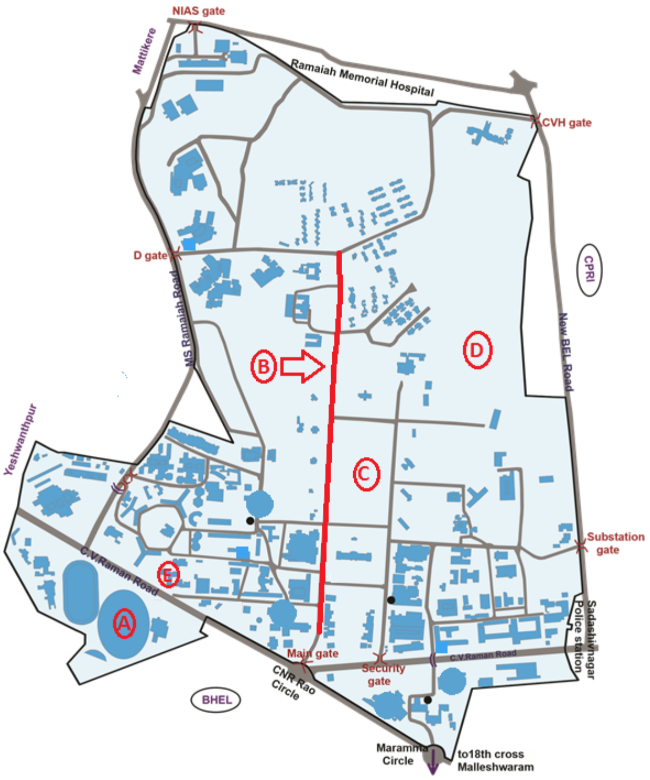

Fig. 5: Locations of field experiments in IISc, Bangalore.

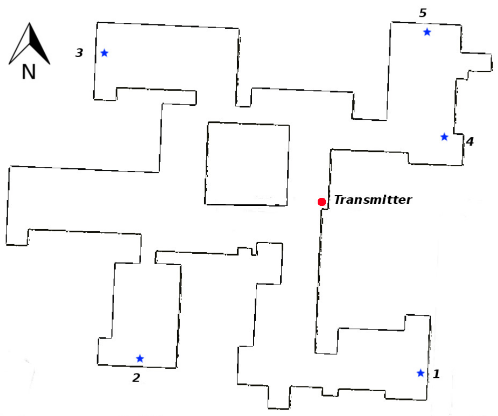

Fig. 6: Tx/Rx positions in NBH; asterisks are Rx locations.

d) Heavily wooded area:* Location D: Jubilee Garden, IISc. Distances between transmitter and receiver: 50 m, 100 m, 150 m, 200 m, and 250 m.

e) Inside building:* Location E: New Boys Hostel (NBH), IISc. Distances between transmitter and receiver: 30 m, 40 m (2 positions), 50 m (2 positions); see Fig. 6.

f) Roof-tops: Locations: 1) NBH to the Centre for Nano Science and Engineering (CeNSE), IISc: distance 813 m; 2) Main building to Centenary Visitors' House (CVH), IISc: distance 1.21 km; 3) Main building to Department of Biological Sciences, IISc: distance 764 m. In Table IX, Link 1 is between NBH and CeNSE, Link 2 is between main building and CVH, and Link 3 is between main building and Department of Biological Sciences.

B. Performance Comparisons

The experimental data are tabulated in Tables VII-X and in Fig. 8-15. The 97.5% confidence intervals at 5 dBm nominal power are in Table VII. Note that a newer pulse antenna was used in the starred locations (tables and plots marked with *). To facilitate comparison, we report pathloss exponents in cases a) and d) for both new and old antennas. Note also that higher RSSI and lower PER are favorable, and higher RSSI will likely yield lower PER.

From the experimental data plotted in Fig. 8 and 12, in the open area, CC1200-DK had higher RSSI than iM880A and zero PER, in comparison to iM880A's less than 1% PER. However, in the straight road and moderately wooded areas, Fig. 10, 14, 11, and 15, iM880A reported lower RSSI, and yet had lower PER. In the heavily wooded area, iM880A generally had higher RSSI and lower PER (except at the 50 m point). In all these locations, iM880A had lower or comparable PER.

Table VIII shows the data for experiments inside a concrete building (NBH), see Fig. 6. Except in Rx location 5, CC1200-DK reported consistently better RSSI performance, but the PERs were comparable, with CC1200-DK faring worse only in location 1 at the 5 dBm level.

On the longest LoS link 2, see Table IX, the CC1200-DK device reported higher RSSI, lower and sometimes even zero PER, but iM880A PER was always less than 1%. Even in other links, the iM880A PER was not too large compared to the CC1200-DK PER except 4.2 % at 5 dBm level on link 1.

Thus, while CC1200-DK appears to have better performance when there is a clear line of sight (LoS) link, iM880A typically has lower or comparable PER even though RSSI values are sometimes higher and sometimes lower than CC1200-DK's values. iM880A uses a spread spectrum modulation scheme which provides better tolerance to interference. It also employs a form of forward error correction that may impart some coding gain. However, there is significant protocol header inefficiency in iM880A which may become an important consideration.

Table X shows values of path loss exponents for different environments, calculated via the best linear fit for the (log) RSSI data with (log) distance, averaged across power levels. In addition, for comparison, we report exponents for the open and heavily wooded areas when using the dipole antennas as well. The exponents for heavily wooded area were calculated without the 50 m values, which appeared anomalous for iM880A. First of all, the pathloss exponents for the dipole antenna were lower than those with the pulse antenna, but so were the RSSI's. The reason for the more dramatic fall in RSSI with distance on the pulse antenna needs investigation. While the pathloss exponents in the open area, straight road, and heavily wooded area are ordered as expected, the exponent for moderately wooded area is higher because of a transition from LoS to non-LoS at around the 150 m distance. We hope that these exponents will be useful in network plannning.

V. Proposed Deployment

Our larger goal is to design an energy efficient and reliable IoT network for water management that connects sensor nodes to a gateway using very few hops. IISc is rather thickly wooded. Wooded area transmission suffers a higher pathloss exponent than LoS communication, as expected. Furthermore, even at a distance of 1.2 km, which is the distance of the farthest OHT from the main building tower, the PER is only between 0.3%-0.5% PER at the lowest 5 dBm setting of our experiments (link 2 data in Table IX). We therefore plan to have an LoS backbone connecting the OHTs to a gateway located at the main building tower. The average distance between the OHTs and the main building is a lower 520 m. All GLRs are located within 200 meters of their nearest OHT. The data from these GLRs can be sent to the relays on the OHT in one hop. The nodes at the OHT can gather these, add their own sensors' data, and transmit to the gateway located at the main building tower in one hop for further uploading to a central server. The proposed plan is indicated in Fig. 7. Which of the two sub-GHz devices is more suitable will depend on whether the header inefficiencies of iM880A can be removed.

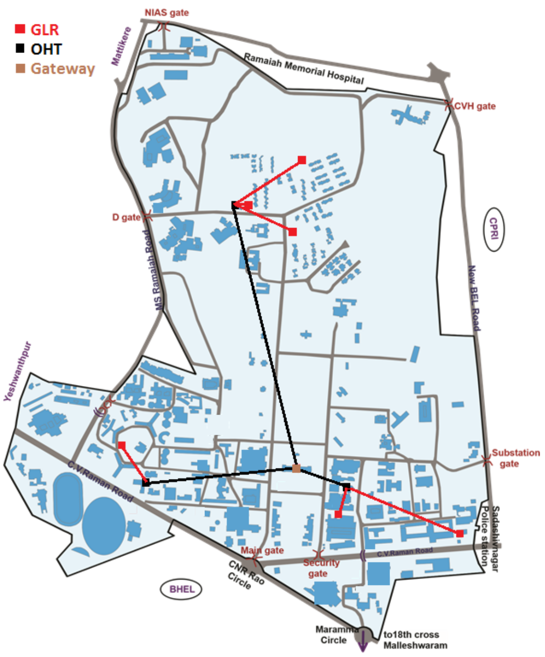

Fig. 7: IoT deployment plan within the IISc campus.

Acknowledgments

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Appendix: Experimental Data

TABLE VII: Size of the 97.5% confidence interval at 5 dBm. Due to space limitations, data for Cricket ground and Jubilee Gardens are reported.

Distance	Open area*		Heavily wooded*	
	CC1200-DK	iM880A	CC1200-DK	iM880A
50 m	0.06026	0.09975	0.07323	0.19783
100 m	0.06034	0.07223	0.32598	0.07882
150 m	0.20042	0.13614	0.15234	0.096096
200 m	0.25799	0.2145	0.14205	0.047052
250 m	0.05059	0.06594	–	0.045601

TABLE VIII: RSSI and PER values inside NBH*.

Position	CC1200-DK						iM880A					
	5 dBm		10 dBm		14 dBm		5 dBm		10 dBm		14 dBm	
	RSSI	PER	RSSI	PER	RSSI	PER	RSSI	PER	RSSI	PER	RSSI	PER
1	-84.5	6.1	-81.2	0.1	-81.5	0	-92	0	-86	0.07	-85	0
2	-98.6	0.3	-93.4	0	-92.5	0.1	-110	0.8	-99	0.07	-95	0
3	-100	0	-94.7	0.1	-92.2	0	-109	0	-103	0	-97	0.4
4	-87.9	0	-83.8	0.2	-79.9	0.1	-97	0.2	-93	0	-88	0
5	-105.8	32.9	-99.3	0.1	-98.1	0	-103	0	-98	0.33	-96	0

TABLE IX: RSSI and PER for roof-top LoS links.

Link	CC1200-DK						iM880A					
	5 dBm		10 dBm		14 dBm		5 dBm		10 dBm		14 dBm	
	RSSI	PER	RSSI	PER	RSSI	PER	RSSI	PER	RSSI	PER	RSSI	PER
1	-83.3	0.1	-77.7	0	-72.5	0	-77	4.2	-75.4	0.5	-73.5	0.1
2	-92.7	0.3	-87.1	0	-83.2	0	-95	0.5	-90	0.6	-88	0.9
3	-85.1	3.6	-79.3	0	-74.8	0	-84.9	0	-81.6	0	-78.3	0.2

TABLE X: Path loss exponents.

Environment	CC1200-DK	iM880A
Open area	2.3	2.8
Straight road	3.9	3.2
Moderately wooded area	4.4	5.9
Heavily wooded area	3.1	3.5
Open area*	3.4	2.5
Heavily wooded area*	4.0	3.6

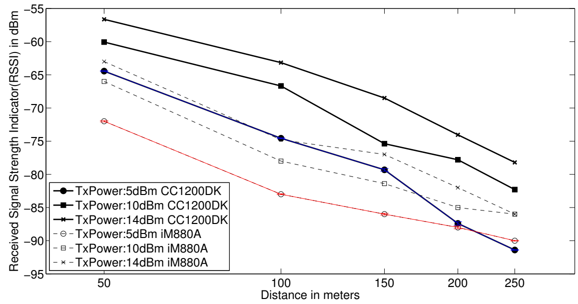

Fig. 8: RSSI vs distance on the cricket ground*.

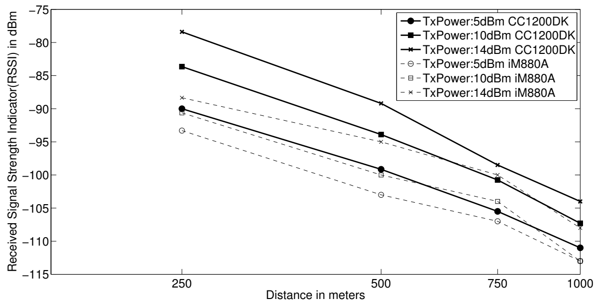

Fig. 9: RSSI vs distance on the straight road.

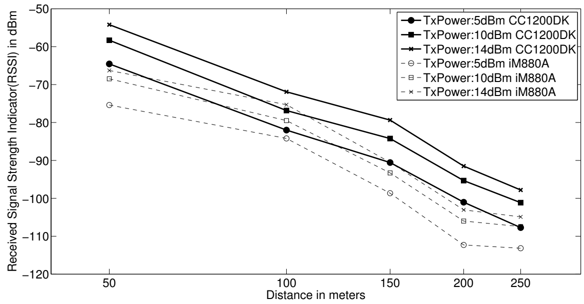

Fig. 10: RSSI vs distance for the moderately wooded area.

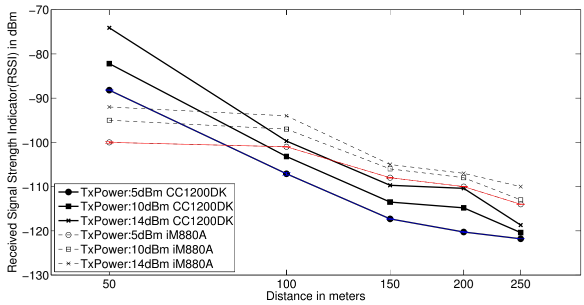

Fig. 11: RSSI vs distance for the heavily wooded area*.

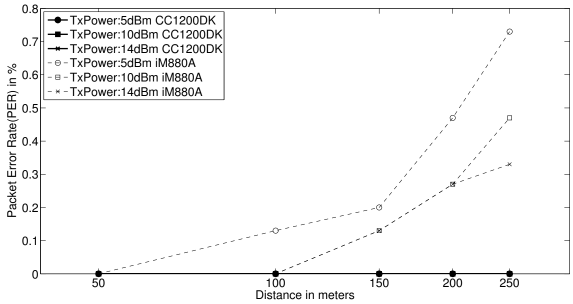

Fig. 12: PER vs distance on the cricket ground*. For CC1200-DK PER was zero for all the locations.

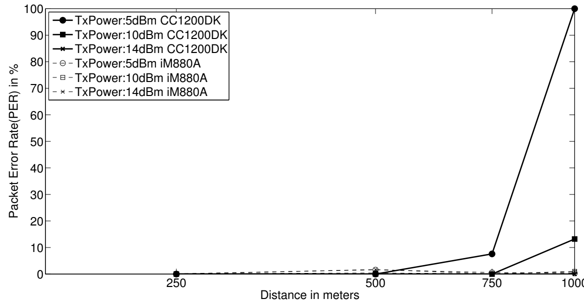

Fig. 13: PER vs distance on the straight road.

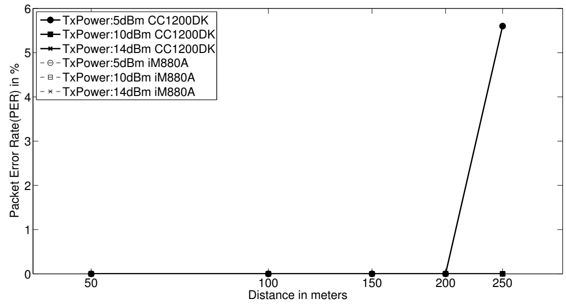

Fig. 14: PER vs distance for the moderately wooded area. For iM880A PER was zero for all the locations.

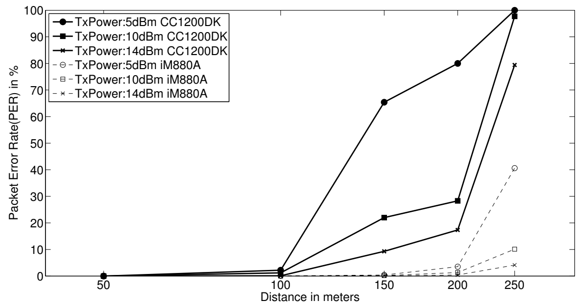

Fig. 15: PER vs distance for the heavily wooded area*.