Discrete Radio Power Level Consumption Model in Wireless Sensor Networks

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Abstract

Research in the wireless sensor network field has been plagued by difficulties in realistic simulations. These difficulties are often the result of non-realistic assumptions which need to be removed from the equation. Recent work in the field has identified realistic radio consumption models, signal strength estimation and that reception cost may be more than the transmission cost. In our work we combine these techniques into a single model for estimating radio power costs. We also investigate the effects of discrete power levels on transmission cost and show that transmission costs do not always increase as the transmission distance increases.

1. Introduction

Wireless sensor networks have been a hot topic for researchers and scholars in recent years. There have been many proposed techniques for modeling radio patterns and calculating the consumed energy costs. [8][7][6] For the most part these papers focus on a single aspect of the problem such as radio range, energy consumption and routing techniques. These papers often make assumptions to keep the problem simple and focused to a specific area.

In this paper, we investigate the combination of several techniques into a single model that will be more realistic and useful for simulations. We attempt to provide a well-integrated model for usage in future work and applications. We also investigate the effects of discrete power levels in radio power models and the effects of the packet size on network quality.

The remainder of this paper is organized as follows. In Section 2, we discuss related work and work that may be affected by the results of our work. Section 3 introduces our proposed radio model and the mathematics behind it. We then introduce an experimental implementation utilizing mote hardware in Section 4. The details from the experiments are then discussed in Section 5.

2. Related Work

Recent related studies on radio modeling and power consumption have focused on introducing realism to existing techniques. Many different radio models exist that aim to introduce realism to calculating connectivity such as [9][8][2]. In these studies, the authors combine previous work, classical radio models with new ideas and findings to create new more realistic radio models. Classical models for radio modeling are isometric and include the free-space propagation model, two-ray model and the Hata model[5]. The problem with classical models are that the path loss in each direction is identical. In [8], the authors show that path loss is not identical in each direction and introduce a new non-isometric model for adding realism.

The area of realistic power consumption has had some recent advancements by work such as [7][6][1]. This work investigates the cost calculations for transmitting and receiving packets. Utilizing realistic cost calculations such as the ones proposed in these papers make for much more accurate simulations and network lifetime estimates. Consumed energy is calculated as the energy consumed per bit transmitted and is usually represented in joules. It's shown in these works that the energy per bit is reduced as the packet size grows which reduces the effect of startup costs.

3. Radio Model

This section introduces a radio model, which dynamically determines which power level setting should be used to transmit between two nodes. Using the power level setting, the cost of transmissions are calculated based off the chip specifications to ensure an accurate estimation.

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3.1. Estimating RSSI

Received Signal Strength Indication (RSSI) is used to determine which power level setting is needed to transmit directly between two nodes. To estimate the RSSI we can use one of the existing radio models, which can be isotropic or anisotropic. Since the main goal of this work is to increase realism of our model, an anisotropic model is used to estimate the RSSI. The model chosen for our implementation is the Radio Irregularity Model (RIM) [8] because of its ability to simulate differences in sending power amongst different pieces of hardware and anisotropic path loss. The RIM model builds upon the simple isotropic models that use Equation 1 by adjusting the Sending Power and Path Loss variables. For Path Loss they introduce a degree of irregularity (DOI) parameter to assign unique path loss in each direction. RIM also adjusted the sending power variable for each node to account for differences in hardware. Using this model we input the sending power level in decibels and the distance between the two nodes to estimate the RSSI when sending between them. The Path Loss calculation performed in RIM can be based on several existing isotropic models such as the Free Space Propagation model, Two-Ray Model or the Hata model[5].

$$RSSI = SendingPower - PathLoss + Fading \quad (1)$$

3.2. Transmission Power Levels

In our work, we focus upon the CC2420 [4] chip for radio communication however we are aware of devices utilizing the CC1000 [3] chip. With both radio chips, one can adjust the transmission power level in order to minimize energy consumption or increase the radio range. These chips have set power transmission levels for use, which consume different amounts of energy. Table 9 in the CC2420 specifications shows the transmission power levels available for the CC2420 radio chip. These values are used in our equations for estimating RSSI and energy consumption.

In most work, authors assume that the power level can be adjusted to the exact needs and calculate the energy cost using these exact values. In reality this is not the case as the radio can only be adjusted to one of the associated power levels and not set to the exact transmission power needed. Using the assumption that there is an infinite amount of transmission levels, previous work makes the assumption that the longer links will cost more to transmit a packet. In many situations two links of different lengths will need to transmit at the same power level setting in order for the packet to be received and therefore the cost to transmit over different distances can be equivalent.

This paper proposes that instead of infinite power levels, the radio must transmit at a set power level according to the chip specifications. To calculate which power level setting should be used we first define a constant, $RSSI_{min}$.

procedure $TransmissionCost(T, R)$

```
1: connected ← false
2: for each i ∈ P do
3:   T.PowerLevel ← i
4:   if (EstimateRSSI(T,R) ≥ RSSI_min) then
5:     connected ← true
6:     break
7:   end if
8: end for
9: return getCost(T.PowerLevel)
```

Figure 1. Discrete power level transmission cost algorithm

Definition 1 *Let $RSSI_{min}$ be the minimum RSSI needed for a potentially successful packet plus the RSSI variation given by the chip specifications.*

The algorithm for determining the transmission cost is shown in Figure 1. The $TransmissionCost$ procedure accepts two arguments which are T and R. T is the mote performing the transmission and R is the mote receiving the packet from T. The procedure begins by initializing $connected$ to $false$ on line 1, which means that these two motes cannot communicate. Lines 2-11 find the ideal power level that T will use to transmit the packet to R. The for loop begining on line 2 starts with the lowest available power level and continues up to the greatest. On line 3, the transmission power level for the transmitter mote is adjusted before estimating the RSSI with the set power level on line 4. If the estimated RSSI is greater than the predefined minimum RSSI, the nodes are able to communicate at this power level. The loop then terminates and the transmission cost at that power level is calculated.

3.3. Transmission Costs

Now that the required power level has been calculated for transmission between two nodes one can determine the transmission cost in joules. Joules are the unit that most simulators use to when determining battery lifetime. Using the CC2420 specifications [4], we can determine the current usage for a given transmission power level in mA.

$$P_T = P_{TO} + P_{PA} \quad (2)$$

Equation 2 is a modified version of Equation 2-1 from [7]. The transmission cost, P_T, is no longer dependent on

the distance between two nodes but rather the chip specifications, packet length and sending power level. P_T is determined by the transmission startup cost, P_{TO}, and the cost of the power amplifier to transmit the packet, P_{PA}.

$$P_{TO} = V \times P_{ROON} \times T_{Startup} \quad (3)$$

Equation 3 defines the startup cost for a transmission. Voltage, V, is determined by the current battery voltage of the transmitter. P_{ROON} is the current usage in Amperes when the radio is in the state of "'Radio On, Oscillator On"'. $T_{Startup}$ is the length of time needed to startup the radio oscillator in seconds.

$$P_{PA} = V \times C_{plevel} \times (L/T_{rate}) \quad (4)$$

Equation 4 defines the cost of the power amplifier for transmitting a packet of length, L, at a power level setting of $plevel$. The term C_{plevel} denotes the current usage in mA at power level, $plevel$. V represents voltage and depends on the status of the batteries in the transmitting node. The cost of PA also depends upon the length of the packet being sent and the transmission data rate. L denotes the packet length in bits and T_{rate} denotes the transmission rate in bits per second. Replacing equations 3 and 4 into equation 2, the complete power consumption for a transmission is shown in equation 5.

$$P_T = V \times (P_{ROON} \times T_{Startup} + C_{plevel} \times (L/T_{rate})) \quad (5)$$

3.4. Reception Costs

The reception cost is calculated based off the CC2420 specifications. The specifications provide the receiving cost as 19.7 mA. This cost is greater than the cost of transmitting at the highest power level setting which uses 17.4 mA. In order to convert current to the energy cost in joules we use formula 6. The cost in joules to receive a packet is P_R. Similar to former formulas, V denotes voltage, L denotes packet length and T_{rate} denotes the transmission data rate. C_R is the current usage for receiving which for the CC2420 radio is 19.7mA.

$$P_R = V \times C_R x \times (L/T_{rate}) \quad (6)$$

4. Experiments

4.1. Experiment A: Effects of Discrete Power Levels

In order to show the effects of discrete power levels, an experiment was needed to verify that this does indeed have effects on the transmission costs. In this experiment, Tmote Sky motes by Moteiv were used for testing. The Tmote Sky motes are equipped with the CC2420 radio which has 8 distinct power level settings. The motes were programmed with nesC on the TinyOS 2.0 platform.

4.2. Implementation Details

For this experiment three motes were used and each had it's own job to perform. The motes were placed in a triangle formation with the packets being transmitted forming a cycle between all motes. The first mote was the base station mote, which was plugged into the computer and acted as the packet gateway to the computer. In order to control the application and record the results there was a Java application running on the local computer. The other two motes were a transmitter and receiver for the experiment. The transmitter would send packets to the receiver where the RSSI and Link Quality Indicator (LQI) were calculated and sent back to the base station. By using this setup, it allowed for the base station to be placed off to the side, avoiding interference from the computer and experiment operator.

The area where the experiment took place was in an open grassy field. The area was fairly flat however at 30-35 meters there was a slight hill which we expected to cause some interference. The motes were placed approximately 40 centimeters off the ground on plastic buckets.

Packet Structure

In order for motes to communicate, a packet structure is needed. One could define a different packet structure for each transmitting mote type such as a control packet from the base station, transmitter packet and receiver packet but in order to make the packets easy to manage a single generic packet type was used. This generic packet is defined as follows:

```
typedef nx_struct GenericMsg {
  nx_uint16_t node_id;
  nx_uint16_t pkt_type;
  nx_uint16_t pkt_data[3]
} GenericMsg;
```

The node_id variable is used to store the ID of the mote transmitting the packet. The pkt_type variable stores which type of packet is being sent which can be a control transmitter or receiver packet. Finally, the pkt_data field stores an array of data that needs to be sent to another mote. Depending on the type of packet being sent some of these data fields may not be needed and are set to 0.

Base Station

The base station mote was programmed using the default BaseStation application that is included with TinyOS 2.0. On the base station computer ran a Java 1.5 application to collect data and control the transmitter mote. The Java application connects to the SerialForwarder, a TinyOS Java tool, using an interface called MoteIF. The MoteIF in-

terface allows for sending and receiving of packets through the base station mote. The RadioExperimenter application allows the user to set the number of packets the transmitter mote should send and at which power level the packets should be sent. When the "Send" button is pressed, a control packet is sent to the transmitter mote and activates the transmitter mote so it begins transmitting packets. When the RadioExperimenter receives a "receiver" packet, the data is logged to a comma separated values file and displayed on the screen.

Transmitter Mote

The transmitter mote needed the ability to receive control packets with the number of packets needed to be sent along with the transmission power level these packets should be broadcast with. None of the default applications had this ability so a custom application was written. When the transmitter is powered on, it does not send any packets until it receives a control packet. When the control packet is received it sets the max number of packets to send and resets packets sent to zero. The Timer interface is used which fires every second allowing transmitted packets to be spaced apart. Whenever a packet is transmitted the number of packets sent is increased by one. Once the number of packets sent is equal to the number of packets to send the transmitter stops sending more packets. In order to adjust the sending power level of the packets, the transmitter must call CC2420Packet.setPower(&pkt, powerlevel). This command passes a reference to the packet the transmitter wishes to send and the power level setting that it should be set at.

Receiver Mote

The receiver mote needs to be able to receive packets from the transmitter, determine the RSSI and LQI, and transmit the data back to the base station for storage. When the packet arrives at the receiver the commands CC2420Packet.getRssi(msg) and CC2420Packet.getLqi(msg) are called in order to retrieve the RSSI and LQI, respectively, of the received packet.

4.3. Experiment Procedure

The procedure used for this experiment was to place the transmitter and receiver motes a starting distance apart such as five meters. Then 10 packets are sent from the transmitter to the receiver with each power level setting available. Once all the power level settings were tested, the receiver mote was moved further away from the transmitter and each power level tested again. This process is continued until no packets are received at the maximum power level setting.

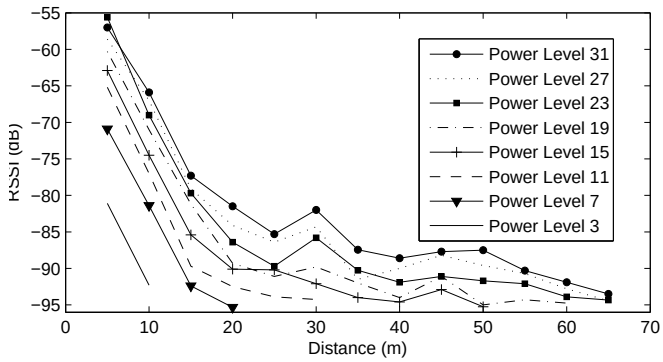

Figure 2. Measured RSSI for various power levels and distances

4.4. Experiment B: Effects of Packet Sizes on Reliability

In addition to the experiment procedure Section 4.3, another experiment was performed to measure the effects of packet size on the packet reception rate (PRR). In this experiment, the receiver was placed at the edge of the communication range, where the RSSI was a constant -94 dB. At this range 100 packets were sent at each packet size of 10 bytes, 20 bytes, 30 bytes and 100 bytes. The average LQI and the PRR rate was calculated with the results. The receiver was then moved to a closer location where the RSSI was a constant -86 dB and the same steps repeated. It should be noted that by default TinyOS restricts the packet size to 28 bytes which we needed to override in order to perform this experiment.

5. Results and Discussion

5.1. Effects of Discrete Power Levels

Most current work assumes that nodes can broadcast at an exact decibel level and calculate the cost of transmission based off that exact value. Using this assumption it's true that it would cost more to transmit over a longer distance. In our experiments, we show that this is not always the case due to discrete power levels. In Table 1, we show the average RSSI, LQI and PRR for the four lowest available transmission power settings and over multiple distances. RSSI and LQI were measured on the receiver node when a packet was received. When a packet was lost it was not included in the calculations for RSSI or LQI. PRR was calculated by the number of packets received divided by the number of packets sent. In this table we can see a dip in the PRR around 35m for all power levels. There was a hill which obstructed the line of sight communication at this distance

which caused the reduced radio communication. Figure 2 shows the RSSI for each power level as the distance increases and was generated from the experimental data obtained in Table 1. On the x-axis is the distance, in meters, between the transmitter mote and the receiver mote. The y-axis marks the average RSSI values, in decibels, that the receiver mote recorded for each distance and power level. Each line on the graph represents the recorded RSSI at a given distance for a transmission power level as indicated in the legend. Where each line on the graph ends is the last point at which packets were received. As with Table 1, we see the effects of the hill on the RSSI. At 30m we can see the RSSI increasing which is due to the mote climbing the hill, which makes communication between the transmitter and receiver better. However at 35m, the mote is descending the far side of the hill which makes communication more difficult and decreases the RSSI.

Table 1 clearly shows the effect of discrete power levels on transmission costs. For instance, at power level 3 the mote can easily communicate with motes within 5 meters and with motes within 10 meters. Since the cost for transmitting at power level 3 does not change depending on the distance the mote is communicating over, the cost to transmit 5 meters and 10 meters are equivalent. This behaviour happens at other power levels as well such as power level 11. This is the lowest reliable power level for distances of 20 and 25 meters in our test environment. Since the power level setting is used to communicate to motes at both 20 and 25 meters away, the cost for transmitting over both these distances are also equivalent. While the costs for transmitting over 20 and 25 meters doesn't change, the quality of the signal is affected as one would expect.

5.2. Effects of packet sizes

In the experiment described in Section 4.4, we tested the relation between the packet reception rate and packet length. From our experiment we found that when transmitting between two nodes on the edge of the connected region, increasing the packet size to greater than 28 bytes decreases the PRR greatly. As shown in Table 2, even when in the connected region larger packet sizes have a negative effect on the link quality for those transmissions. From [1] we know that as the packet size increases, the energy per bit of data decreases as the radio startup and overhead costs are shared amongst more data bits. With the results from our experiment we see that as the packet size increases the quality of the link decreases, resulting in a tradeoff between network link quality and transmission energy costs. One must choose a packet size that best matches the requirements of the network. For networks using links in the transitional region, we suggest that packet sizes of 28 bytes or less to are used avoid the large dropoff in the packet reception rate.

6. Conclusion

The radio model presented to calculate the cost of a transmission utilizes discrete power levels to improve the accuracy of cost estimations and introduce added realism to the cost calculations. There are not an infinite number of power level settings with the current sensor devices and as such there is no reason why it should be assumed so. These assumptions lead to radio models that assume transmission power is directly proportional to transmission distance which this work has proven is not the case. We also presented results that show as the packet size increases the packets are more susceptible to errors which decrease the network quality.

Our future work includes applying this radio model to single and multihop routing for low power wireless sensor networks in petroleum environments. These are radio harsh environments due to physical machinery interference, noise, vibrations, extreme temperatures and humidity. These challenges need to be overcome before commercial, off the shelf products for these environments can become a reality.

References

[1] Q. Cao, T. He, L. Fang, T. Abdelzaher, J. Stankovic, and S. Son. Efficiency centric communication model for wireless sensor networks. In *INFOCOM 2006: 25th IEEE International Conference on Computer Communications*, pages 1–12, 2006.

[2] A. Cerpa, J. L. Wong, L. Kuang, M. Potkonjak, and D. Estrin. Statistical model of lossy links in wireless sensor networks. In *IPSN '05: Proceedings of the 4th international symposium on Information processing in sensor networks*, page 11, Piscataway, NJ, USA, 2005. IEEE Press.

[3] Chipcon AS. *Chipcon SmartRF CC1000, Single Chip Very Low Power RF Transceiver*, 04 2004.

[4] Chipcon AS. *Chipcon SmartRF CC2420, 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver*, 2006.

[5] P. M. Shankar. *Introduction to Wireless Systems*. John Wiley and Sons, Inc., 2001.

[6] A. Y. Wang and C. G. Sodini. A simple energy model for wireless microsensor transceivers. In *GLOBECOM '04: Global Telecommunications Conference 2004*, pages 3205–3209, 2004.

[7] Q. Wang, M. Hempstead, and W. Yang. A realistic power consumption model for wireless sensor network devices. In *SECON '06: Sensor and Ad Hoc Communications and Networks*, pages 286–295, 2006.

[8] G. Zhou, T. He, S. Krishnamurthy, and J. A. Stankovic. Impact of radio irregularity on wireless sensor networks. In *MobiSys '04: Proceedings of the 2nd international conference on Mobile systems, applications, and services*, pages 125–138, New York, NY, USA, 2004. ACM Press.

[9] M. Zuniga and B. Krishnamachari. Analyzing the transitional region in low power wireless links. In *SECON '04: Sensor and Ad Hoc Communications and Networks*, pages 517–526, 2004.

Table 1. Experimental results of average RSSI (dB), LQI and PRR as distance and transmission power levels change

Distance	Power Level 3			Power Level 7			Power Level 11			Power Level 15		
	RSSI	LQI	PRR	RSSI	LQI	PRR	RSSI	LQI	PRR	RSSI	LQI	PRR
5m	-81.1	107.1	1.0	-70.9	106.8	1.0	-65.2	107.3	1.0	-62.9	107.6	1.0
10m	-92.3	95.7	1.0	-81.4	106.8	1.0	-77	107.2	1.0	-74.5	107.5	1.0
15m	–	–	–	-92.4	95.9	1.0	-89.7	103.4	1.0	-85.4	106.0	1.0
20m	–	–	–	-95.3	69.7	0.3	-92.5	93.5	1.0	-90.1	101.8	1.0
25m	–	–	–	–	–	–	-93.9	84.3	1.0	-90.2	101.6	1.0
30m	–	–	–	–	–	–	-94.25	77.625	0.8	-92.1	94.3	1.0
35m	–	–	–	–	–	–	–	–	–	-94.0	79.3	0.4
40m	–	–	–	–	–	–	–	–	–	-94.6	75.4	0.5
45m	–	–	–	–	–	–	–	–	–	-92.9	92.3	1.0
50m	–	–	–	–	–	–	–	–	–	-92.25	70.4	0.8

Distance	Power Level 19			Power Level 23			Power Level 27			Power Level 31		
	RSSI	LQI	PRR	RSSI	LQI	PRR	RSSI	LQI	PRR	RSSI	LQI	PRR
5m	-60.3	107.3	1.0	-55.6	107.4	1.0	-58.6	107.1	1.0	-57.0	107.0	1.0
10m	-71.0	107.3	1.0	-69.0	107.5	1.0	-67.0	107.3	1.0	-65.9	107.3	1.0
15m	-81.2	106.4	1.0	-79.7	106.5	1.0	-79.1	106.8	1.0	-77.3	106.2	1.0
20m	-89.3	104.3	1.0	-86.4	106.1	1.0	-84.1	106.4	1.0	-81.5	106.1	1.0
25m	-91.1	98.5	1.0	-89.7	101.5	1.0	-86.4	104.1	1.0	-85.3	103.1	1.0
30m	-89.8	100.7	1.0	-85.8	104.8	1.0	-84.3	105.5	1.0	-82.0	105.0	1.0
35m	-92.0	93.9	0.9	-90.3	99.4	0.8	-91.5	96.0	0.6	-87.4	102.9	0.9
40m	-94.0	83.7	0.7	-91.9	97.5	1.0	-90.0	101.4	1.0	-88.6	103.5	1.0
45m	-91.1	99.2	1.0	-91.9	100.5	1.0	-88.2	103.0	1.0	-87.7	103.5	1.0
50m	-95.0	76.3	0.6	-91.7	96.2	1.0	-89.6	103.3	1.0	-87.5	104.0	1.0
55m	-94.3	79.7	0.7	-92.1	95.1	1.0	-90.7	101.4	1.0	-90.3	101.9	1.0
60m	-94.8	77.5	0.4	-93.9	85.8	1.0	-92.8	90.1	1.0	-91.9	94.0	1.0
65m	–	–	–	-94.3 dB	77.0	0.3	-94.4	70.1	0.7	-93.5	82.0	0.2

Table 2. Experimental results of packet size vs packet reception

Packet Size	Connected Region			Transitional Region		
	Avg RSSI	Avg LQI	PRR	Avg RSSI	Avg LQI	PRR
10 Bytes	-85.91 dB	105.79	1.0	-93.93 dB	83.87	0.95
20 Bytes	-85.88 dB	106.19	1.0	-93.98 dB	83.81	0.93
30 Bytes	-85.89 dB	105.02	1.0	-94.00 dB	81.97	0.79
100 Bytes	-85.93 dB	88.07	0.96	-94.01 dB	79.99	0.77