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Improving Link Quality Estimation in Zigbee Networks

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ABSTRACT

IMPROVING LINK QUALITY ESTIMATION IN ZIGBEE NETWORKS

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Northern Illinois University, 2019
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Estimation of links in a Wireless Sensor Network and using such estimates to decide between all the multiple paths available in a network is important. There are several link estimation methods available. This thesis evaluates the performance of PRR based method (P-success method), suggested in the ZigBee specification and LQI based method (LQI method) used by different organizations, in various scenarios. The performance of these two link cost estimation methods are also compared under Wi-Fi interference. This comparison is done using a network simulator (NS3). It is observed that, if there is no Wi-Fi interference, both the P-success and LQI methods perform very similarly. In the presence of Wi-Fi interference, P-success method performs better than the LQI method. Based on the observations from the comparison of the two link cost estimation methods, this thesis proposes an improvement by combining the two existing methods into a new method called P_1 + LQI method. Performance of the new method was evaluated by comparing it with P-success and LQI method. This new method (P_1 + LQI) performs similarly as the P-Success method in scenarios with Wi-Fi interference, and perform similarly, or better, than the LQI-based method in scenarios without Wi-Fi interference.
IMPROVING LINK QUALITY ESTIMATION IN ZIGBEE NETWORKS

BY

SRIKAR MEKA

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE

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Thesis Director:
Dr. Benedito Fonseca Jr.
ACKNOWLEDGEMENTS

I would like to sincerely thank Dr. Benedito Fonseca for his constant support and efforts to guide me throughout the process to accomplish this thesis. His dedication and hard work have provided a path for the thesis to move forward to make it a success. I would also like to thank my committee members, Dr. Mansour Tahernezhadi and Dr. Lichuan Liu, for their valuable suggestions to make the project a successful one.

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I would like to express my sincere gratitude to my parents, my friends and other researchers for their encouragement and continuous support throughout my journey at NIU. My work would not have been possible without them. Thank you.

Srikar Meka
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CHAPTER 1
INTRODUCTION

1.1 Background on Wireless Sensor Networks (WSN)

A wireless sensor network (WSN) is a wireless network consisting of spatially distributed devices equipped with sensors to monitor physical or environmental conditions [1]. There are many applications for WSNs. For instance, WSNs can be used in a home environment to monitor to the status of various appliances such as televisions, refrigerators, lights, door locks, power meters, etc.

Devices in a WSN need communication protocols to transmit information to a central unit or device that processes the information. There are many communication protocols used in WSNs, such as ZigBee [2], Bluetooth [3], Wi-Fi [4]. In this thesis we focus on ZigBee.

Figure 1: Example of a WSN.
ZigBee is an IEEE 802.15.4 standard which provides communication protocols in networks with low power radios. They are particularly suitable for home automation [5]. In ZigBee, all the devices try to connect with each other, which helps other devices to communicate even if one device stops working [1].

In a network, one or more links combined makes a path or route. Each link has its own cost to transmit data through it and, the cost of all the links are summed to determine the cost of the path. The cost of each path is what differentiates each of the available paths.

Routing is the process of choosing a path by a node, among all the available paths, in order to exchange data among the devices (nodes) of the network. Often, such path will be multi-hop paths; i.e., will be paths in which other nodes of the same network are used to relay packets from source node to the destination node. Multi hop routing is used in networks in which a node cannot
transmit a packet to the destination node directly; i.e., the radio range of transmissions is smaller compared to the dimensions of the network [1]. Fig.3 shows multiple multi-hop paths available in a WSN.

The goal of routing is to select a path with the least cost among all the paths available. It is important to observe that the cost of the links are not known to the nodes beforehand; therefore, nodes need to estimate them and use such estimates to decide between all the multiple paths available.

![Diagram of WSN with multiple paths available](image)

**Figure 3**: Example of a WSN with multiple paths available.

### 1.2 Scope of the Thesis

This thesis focuses on methods to estimate link and path costs in order to inform routing algorithms in ZigBee networks.

There are three main contributions for this thesis:

- This thesis compares two existing link cost estimation methods in various scenarios.
• This thesis compares the performance of the two link cost estimation methods under Wi-Fi interference. This comparison is done using a network simulator (NS3) and has not done before.
• Based on the observations from the comparison of the two link cost estimation methods, this thesis proposes an improvement by combining the two existing methods.

1.3 Literature review

This section describes the main papers that proposed methods to estimate the cost or quality of links in WSNs.

The authors in [6] discuss the fundamental concepts of link quality estimation like

• **PRR (Packet Reception Ratio):** Packet Reception ratio (PRR) is defined as number of packets successfully received to the total no of packets sent.

• **RSSI (Received Signal Strength Indicator):** Received signal strength indicator (RSSI) is a measurement of the power present in a received radio signal. RSSI is usually invisible to a user of a receiving device.

• **SINR (Signal to Interference + Noise Ratio)**

• **LQI (Link Quality Indicator):** The Link Quality Indicator is a metric that reflects the current quality of the received signal. It is dependent on SINR.

The authors in [6] also provide an analysis of empirical characterization of low-power links in WSN. Based on simulation and experimental work, the authors show a novel taxonomy and classification of an existing link quality estimators and mentions their performance. They define
interference in ZigBee networks and classify them into external and internal interferences. They also discuss the interference of IEEE 802.11b (Wi-Fi) and IEEE 802.15.1 (Bluetooth) with ZigBee, discussing some interesting observations made by Srinivasan et al. [7], that the Wi-Fi interference affects the link estimation and also leads to packet losses. They mention that the Wi-Fi transmission power is hundred times stronger than the ZigBee transmission power, highlighting the observation made by Liang et al. [8] that, if a ZigBee transmitter is close to a Wi-Fi transmitter, then the Wi-Fi node may suspend its transmission due to high channel energy.

In [9], the authors propose a new metric for multi-hop wireless networks called Expected Transmission count metric (ETX). Route selection using ETX accounts for link loss ratios, the asymmetry of the loss ratios in the two directions of each link, and the reduction of throughput due to interference among the successive hops of a route. Measurements on a wireless test-bed show that ETX finds routes with significantly higher throughputs than a minimum hop-count metric, particularly for paths with two or more hops. In more details, the ETX of a link is calculated using the forward and reverse delivery ratios of the link. The forward delivery ratio, $d_f$, is the estimated probability that a data packet is successfully delivered; the reverse delivery ratio, $d_r$, is the probability that the ACK packet is successfully received.

$$ETX = \frac{1}{d_f \times d_r}$$

In [10], the authors identify valuable information from each layer that can assist in link estimation and experimentally diagnose failure cases each layer cannot identify individually. It also talks about defining a set of narrow interfaces that provide 4 bits of information: 1 from the physical layer, 1 from the link layer, and 2 from the network layer. These bits of information are protocol independent, thereby keeping layers decoupled and avoiding unforeseen dependencies.
that hinder network evolution. A prototype estimator that uses these interfaces and evaluate its improvement such as packet delivery costs & delivery ratio over current approaches is presented.

In [11], the ZigBee specifications suggest a method for link estimation. Similarly to the method presented in [9], the ZigBee specifications suggest that link costs be estimated from the probability of successful packet delivery in the link. Since this is one of the methods being studied in this thesis, more details are provided in Chapter 2.

Still in ZigBee networks, [12] describe an alternative method for link estimation that relies solely on SINR measurements on packets received. These measurements are mapped into a metric called LQI (Link Quality Indicator). The LQI is an 8-bit number proposed in the IEEE 802.15.4 specification that reflects the SINR of received packets. Since this is the other method being studied in this thesis, more details are provided in Chapter 2. The table 1 provides pros and cons of the literature and also compares it with the thesis being proposed.
Table 1: Pros and cons of the literature review and comparing it with the thesis being proposed.

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| A high-throughput path metric for multi-hop wireless routing [9]. | • This method proposes a new metric called ETX for the Link Quality Estimation, which uses probability of forward and backward delivery ratios through that link, to estimate the link cost. The authors did not evaluate the performance of their method under Wi-Fi interference.  
• In relation to this thesis, it does not evaluate ETX metric; however, the ETX metric is similar to the PRR metric suggested in the ZigBee specification, which is evaluated in this thesis under the P-success method. |
| Four-bit wireless link estimation [10]. | • The authors in [10] identify valuable information from each layer that can assist in link estimation and experimentally diagnose failure cases each layer cannot identify individually. The authors did not evaluate how interference would affect such information during link estimation.  
• In relation to this thesis, the method $P_1 + LQI$ that this thesis proposes also uses information from various layers (physical and network layers) to estimate link costs; and the results obtained in Chapter 6 confirm that the use of information from various layers can be beneficial to the link estimation, even in the presence of interference. |

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<td>• This thesis compares the performance of two link quality estimators, one proposed by the specifications (P-success method) and another used by companies (LQI method), with and without an external Wi-Fi interference. The analysis presented in this thesis shows that different link quality estimation methods lead to different performance in certain situations.</td>
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CHAPTER 2

OVERVIEW OF ZIGBEE

2.1 ZigBee

ZigBee is a low power wireless communication standard that defines protocols to communicate in Personal Area Networks such as Internet of Things applications and home automation with a low data rate. ZigBee uses multi hop routing to increase the range of the network. Mesh topology is used in ZigBee, as shown in Fig.4. So, all the nodes acts a router to the neighboring nodes [13].

Figure 4: Example of a WSN with Mesh Topology.
2.2 Architecture of the ZigBee Protocol

ZigBee protocol architecture has ZigBee Device Object (ZDO), Application support subsystem (APS), Network Layer (Nwk), IEEE 802.15.4’s MAC and Physical layers as shown in Fig. 5 [14].

**ZigBee Device Object (ZDO)** manages, controls and interfaces all the applications objects. It controls the process of initiation of network discovery. ZDO communicates through clusters which has all basic functionalities of the applications of the same type.

**Application support subsystem (APS)** stores the binding table which has the list of end devices and its clusters. It encapsulates the application messages and provides reliable data transfer through acknowledgements.

**Network layer (Nwk)** establishes communication path between devices. The process of network discovery and routing are defined by Nwk layer. There are 2 main routing methods used in ZigBee and will be discussed in the section 2.5. Nwk layer also controls the process of end devices joining and leaving the network.

**MAC layer** controls the accessing of channel using Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) process.

**Physical layer (Phy)** takes control of transmitting and receiving the packets through the channel. It also helps the upper layers by providing the quality of the channel.
ZigBee operate on the same unlicensed ISM band (2.4GHz) in which Bluetooth and Wi-Fi networks operate [6]. Due to the operation in the same frequency band, interference from Wi-Fi may happen in WSN, which may lead to packet losses during transmission. These packet losses would be reflected in link quality metrics such as delay in packet delivery and could also impact routing decisions, as will be discussed later.

### 2.3 Link Status Messages

In ZigBee, nodes transmit Link Status messages. These messages are periodically transmitted by each routing node of the network and are used to assist in routing decisions [11].
In each Link Status message, a node broadcasts to its neighbors its current view of the links to each of its neighbors. More precisely, the Link Status message contains a list of all neighbors of the node and contains the incoming cost of the link from each of its neighbors.

The incoming cost of each link is measured by the node using link estimation methods. There are two ways of estimating incoming link costs, as described next.

2.4 Link Quality Estimator and path selection

2.4.1 ZigBee Algorithm (P-success method)

The ZigBee specifications suggest the following path cost metric: First, the probability of successful packet delivery \(P_l\) for each link is estimated from all the link status messages and are mapped into costs as shown in the equation (1) [11].

\[
C{l} = \min\left(7, \text{round}\left(\frac{1}{P_l}\right)\right)
\]  

(1)

where \(P_l\) is defined as the probability of successful packet delivery on the link \(l\).

When selecting routes, a node compares the costs of the paths to determine the best route for a particular destination node. Each link in the path has a cost, known as the link cost, and link cost values are summed to obtain the cost for the path as a whole. The path with the least cost will be selected by the node [11].

More formally, if we define a path \(P\) of length \(L\) as an ordered set of devices and a link, as a sub-path of length 2, then the cost of the path \(C\{P\}\) is

\[
C\{P\} = \sum_{i=1}^{L-1} C\{[D(i), D(i + 1)]\}
\]
where $D(i)$ is the i-th node in the route and $C([D(i),D(i+1)])$ is the cost to transmit on the link between $D(i)$ and $D(i+1)$.

$P_l$ can be considered the true metric to determine the cost of link; however, $P_l$ is unknown to nodes and nodes need to estimate it, as discussed next.

### 2.4.1.1 Estimating the Probability of Successful Transmission in the link

One way for a node A to estimate the $P_l$ of a link from B to A is to count how many packets node A received from node B. $P_l$ is then estimated by computing the ratio between the number of packets received to the number of packets transmitted by B.

But how can node A know how many packets node B transmitted? Node A can obtain this information from the Link Status messages, since every node must send a known number of messages per period of time. More precisely, node A can estimate the $P_l$ of the link from node B to node A by counting how many link status messages it received from B in a period of time and dividing it by the number of link status messages that it should have received in the period.

The time between link status messages is a configurable parameter in a ZigBee network. In this thesis, it is considered that nodes transmit one link status message every second and a node estimates the $P_l$ of a link with its neighbors based on the number of link status messages received in the last 20 seconds.
2.4.1.2 Mapping $P_l$ estimates into Link Cost

Once the probability of successful packet delivery ($P_l$) is estimated, it must be mapped into a link cost. The ZigBee specifications specify that link costs be an integer between 0 and 7, such that it can be transmitted in only 3 bits.

In this thesis, $P_l$ is mapped into the link cost $C[l]$ using the formula in equation (1) in section 2.4.1.1.

In further discussions, the method of computing path costs with link costs determined from estimates of $P_l$ from the ratio of link status messages received to the number of link status messages expected is referred to as the P-success or $P[success]$ method.

2.4.2 LQI-based method

As mentioned in 2.4.1, determining path costs from $P_l$ estimates is provided in the ZigBee specifications as a suggestion. Manufacturers are allowed to design and adopt their own link quality estimation algorithms. One example can be found in [12], which describes a method to estimate link costs based on LQI measurements. In this thesis, this method will be referred to as the LQI-based method.

In the LQI-based method, the metric used to estimate the links is Link Quality Index (LQI). The LQI metric is an integer number that ranges from 0 to 255. LQI is a metric that reflects the quality of the link from the SINR of the received signal through that link.
In this thesis, the LQI-based method estimates the average LQI from every packet transmitted through the link [12]. Then the incoming link cost of the neighbor is computed using this value from a look up table. The look up table used in this thesis is as follows:

Table 2: LQI into cost conversion Look up Table

<table>
<thead>
<tr>
<th>Avg LQI(LQI)</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>239&lt;LQI&lt;255</td>
<td>1</td>
</tr>
<tr>
<td>206&lt;LQI&lt;=239</td>
<td>2</td>
</tr>
<tr>
<td>195&lt;LQI&lt;=206</td>
<td>3</td>
</tr>
<tr>
<td>185&lt;LQI&lt;=195</td>
<td>4</td>
</tr>
<tr>
<td>174&lt;LQI&lt;=185</td>
<td>5</td>
</tr>
<tr>
<td>170&lt;LQI&lt;=174</td>
<td>6</td>
</tr>
<tr>
<td>LQI&lt;170</td>
<td>7</td>
</tr>
</tbody>
</table>

It should be noted that the mapping of average LQI into link costs is not specified in the ZigBee specifications. For this thesis, the values of Table 2 were obtained as follows: simulations were performed in which two nodes exchanged packets at a certain distance. The probability of successful packet delivery and the average LQI at the receiver were
computed for the distance. The link cost associated with the average LQI was then set as the same link cost that obtained by equation (1) with the estimated probability of successful packet delivery. The process was repeated for various distances.

In further discussions this method is referred to as the LQI method.

It is important to not confuse the LQI-based method with the LQI metric available from the physical layer in any packet received.

### 2.4.3 Relation between P-success and LQI method

It should be highlighted that both P-success and LQI methods rely on the same network, MAC, and Physical layer procedures defined in the ZigBee specifications. This means that both methods will be correlated and will depend on the performance of lower layers. For instance, a link that has severe interference will result in higher link costs in both the P-success and the LQI methods. The only difference between the two methods is the way in which they estimate the cost of the link for route decision purposes. In the LQI-based method, the LQI metric provided by the Physical layer is directly used to map into a link cost. In the P-success method, the LQI metric is still available; however, it is not used to estimate the link cost. Instead, the P-success method estimate the link cost from the ratio of link status messages received.

### 2.5 Routing Methods in ZigBee

In ZigBee, there are 2 main routing methods: unicast (table) routing, and Many-to-one (M2O) routing. In this thesis, the focus is on the M2O routing.
In both methods, nodes establish routes by first transmitting a Route Request message.

**Route Request messages (RREQ)**

The Route request message allows a source node to discover a route to the destination node with the help of neighboring nodes. The neighboring nodes help the source node by rebroadcasting the RREQ message.

Each RREQ message carries the link costs accumulated in the path. Before a node rebroadcasts a RREQ message, it first extracts the accumulated link cost from the RREQ header and adds to it the incoming cost to the previous node. Thus, when the destination node receives the RREQ, the RREQ header would contain the path cost between the destination and the source.

It is important to highlight that a node may receive multiple RREQ messages, one for each possible route towards the source node. The path cost present in each RREQ message helps a node to select the best path available to the source node [11].

**2.5.1 Many-to-one (M2O) Routing**

In M2O routing, all the nodes store the path to the central node (concentrator). In M2O routing, the concentrator periodically sends a RREQ message to all the nodes in the network and this establishes a single route table entry in each node by storing the next hop. With a single M2O RREQ, the next hop is stored in the route table of a node, saving high amount of memory in the nodes [14].
A route record message is sent by the destination node, with a route to the concentrator, for every RREQ message sent by the concentrator. The concentrator uses this path in the reverse order to send packets out to each node in the network. Concentrator places this path in the header of the packet and all the nodes uses this path in the header to relay it to the destination [11].

To illustrate M2O routing, consider the example network shown in Fig.6.

Figure 6: Example of a WSN with Door lock application

Here in this WSN, node 5 is configured to act as the ZigBee Concentrator. NWK layer of the concentrator creates a RREQ message and Nwk layers of other nodes rebroadcasts the RREQ message. After joining the network, Node 5 starts to periodically broadcast RREQ messages. When Node 4 receives the Many-to-One RREQ message, it creates an entry in its routing table indicating a many-to-one route towards Node 5 that has Node 5 as the next hop; and rebroadcasts the RREQ message.
When Node 2 and 3 receive Node 4’s RREQ message, they create an entry in their routing table indicating a many-to-one route towards NWK 5 that has NWK 4 as the next hop; and rebroadcast the RREQ message. When Node 7 receives NWK 3’s RREQ message, it creates an entry in its routing table indicating a many-to-one route towards NWK 5 that has NWK 3 as the next hop.

As Node 2, 3, 4, and 7 (devices with routing capability) receive the Many-to-One RREQ message, they will send a unicast Route Record (RREC) command towards Node 5. This message is sent using source routing; thus, the RREC message sent by Node 7 reaches Node 3, which attaches its address to the NWK header before forwarding the RREC message towards Node 4, which attaches its address to the NWK header before forwarding to NWK 5. When NWK 7’s message arrives at Node 5, NWK 5 stores the route record 4-3-7 towards Node 7 in its Source Route Table.

In this thesis, the various link quality estimation methods considered assume that the ZigBee network uses M2O routing.
CHAPTER 3

METHODOLOGY

3.1 Network Simulator3 (NS3)

NS3 is a simulator which is used to simulate network topologies and examine the working of different communication protocols [15]. NS3 is made up of two or more nodes (devices), which may have multiple applications. They simulate user behavior and generate traffic in the network. Each node has different layers and each layer respectively have different functions.

NS3 is a discrete event simulator; i.e., objects generate events to other objects, which process the events and in turn generate further events to other objects. This is the main way in which layers communicate among themselves; and events are used to process various state machines within each protocol layer.

NS3 has the Packet and the Packet Header classes, which represent the information that is generated in an application and travels across the layers, collecting each layer information in their header. Packets are then transmitted to other nodes using a communication channel. NS3 can simulate wireless and wireline channels. The channel is also an object; nodes connect to the channel object; and NS3 manages the transmission of packet objects from the transmitter to any receiver connected to the channel. The location and quantity of nodes can be set in an NS3 script. Two different standards or technologies can be simultaneously simulated and their effects on each other can be studied. For example, ZigBee and Wi-Fi can be simulated together and the
interference of Wi-Fi with ZigBee can be studied. Noise and interference are also considered by NS3.

3.2 Scenarios Simulated

In this thesis, the various link estimation methods are first evaluated in small scenarios. Such small scenarios allow a better understanding of the underlying mechanisms that are influencing the link estimation methods. Later, the estimation methods are evaluated in random scenarios.

3.2.1 T-Scenario

Figure 7: T-Scenario considered in some of the simulations.

The icon 📡 represents Wi-Fi nodes.
The T-Scenario represented in Fig.7 was used to study the performance of the link estimation methods discussed in the section 2.3. In this scenario, Node 0 is the concentrator and node 3 needs to decide between routes 3-2-0 and 3-1-0 to transmit its messages to node 0.

The motivation for this scenario is that scenarios in which a source node has an option of choosing between two paths to transmit to a destination is most commonly found. In this scenario, where Node 3 can either choose Node 1 or Node 2 to route the packet to Node 0, in the shape of T, making it a T-Scenario. T-Scenario is a well-controlled scenario and is used to better understand how the estimations behave.

### 3.2.2 H-Scenario

![Diagram](image)

Figure 8: H-Scenario considered in some of the simulations.

The icon represents Wi-Fi nodes.

The H-Scenario represented in Fig.8 was used to study the performance of the link estimation methods discussed in the section 2.3. In this scenario, Node 0 is also the
concentrator and node 3 needs to decide between routes 3-2-0 and 3-5-1-4-0 to transmit its messages to node 0.

The motivation for the H-scenario is as follows: in the T-Scenario discussed in the section 3.2.1, as the distance $d_2$ increases, the chance of Node 1 losing the RREQ message from node 0 increases and node 3 would then have just the route 3-2-0 available. Having just one route available does not allow the study of the differences between different link estimation methods. By considering nodes 4 and 5, the route 3-5-1-4-0 becomes available even if node 1 is not able to receive the RREQ directly from node 0, allowing the comparison between link estimation methods. The H-Scenario is also a well-controlled scenario.

### 3.2.3 Random-Scenario

![Diagram](image)

**Figure 9:** Random Scenario considered in some of the simulations.

The icon represents Wi-Fi nodes.
In order to evaluate the performance of link estimation methods in more realistic scenarios, a Random Scenario was also used to study the performance of the estimation methods considered in this thesis. In this scenario, nodes 0, 2 and 3 are placed as shown in the above Fig.9, to make sure that there is at least one route with a single hop. The remaining three nodes are placed randomly by the simulator during the simulation.

3.3. Performance Metrics

In order to evaluate the link cost estimation methods discussed in the section 2.3, the following performance metrics were used:

- Delay to send commands and receive response

  Delay is one of the most important factors in evaluating the performance of a ZigBee network. In this thesis, the metric used is the delay to send commands and receive responses by a node. If a method provides higher delay in sending commands and receiving responses, then the method is considered inferior than another method with lower delay.

  For example, if ZigBee is used in a Security system, all commands and responses should be received by the devices with the least delay possible. Another example to illustrate the importance of delay is home automation using ZigBee. The functions such as turning on or off a device, changing the temperature of the room should be performed with the least delay possible. So a link cost estimation method which provides the least delay should be preferred in the ZigBee.
• **Ratio of packets sent on the desired route**

  The best path among all the available paths of the network must be selected to send packets with the least delay and least cost. Selecting the best route in case of Wi-Fi interference is very crucial because, if a bad path is chosen then the packets are prone to interference and there is a high probability of losing them. So, selecting the best route more often and sending packets through this route is the other important parameter to evaluate the estimation methods.

  It is important to mention that, in ZigBee, data throughput is not the main goal because, in many applications, nodes don’t have much information to send.
CHAPTER 4
COMPARISON OF P-SUCCESS METHOD & LQI METHOD WITH NO WI-FI INTERFERENCE

Although ZigBee Specification specifies P-success method, which uses probability of successful packet delivery ($P_I$) to estimate the costs of the links and select the best path, others have proposed the LQI method to estimate the best path discussed in the section 2.3.2 [12]. It is unclear which method would perform best in various scenarios and this is one of the motivations for this thesis. This chapter deals with the study and comparison of the P-success method & LQI method with no Wi-Fi interference.

The chapter begins by studying the performance of both methods in a well-controlled scenario (the T-scenario), with nodes in very specific locations. The purpose of studying the two methods in a well-controlled scenario is to better understand how they behave. Later, this thesis compares the performance of both methods in the more realistic Random-Scenario.

4.1 T-Scenario ($d_2=68m$)

The T-Scenario, described in the section 3.2.1, was simulated in NS3 by placing the Node 0 at (-80, 0), node 2 at the origin (0, 0), Node 3 at (80, 0) and Node 1 at (0, -68) on the coordinate axes, with no interference. In order to average the randomness of the route discovery procedure
and the channel access method, the T-Scenario was simulated with 30 different seeds for both the methods.

Figure 10: Box Plot of delay in a T-Scenario (d=68m) with 0% Wi-Fi channel Time, by using P-success and LQI methods.
Figure 11: Box Plots of ratio of packets sent on the desired route in a T-scenario ($d_2=68m$) with 0% Wi-Fi channel time, by using P-success and LQI methods.

Discussion

Fig.10 and Fig.11 depict box plots of delay to send and receive packets, and the ratio of packets sent on the best route (3-2-0) respectively in both P-success and LQI methods. The red line in the middle represents the median value, while the top and bottom edges of the box represents the 75th and 25th percentiles respectively. The top most and the bottom most lines indicate maximum and minimum values respectively (not considering outliers).

From Fig.10, it is possible to see that the delay in the LQI method is smaller when compared to the delay observed in the P-success method but, it is very minute. The reason for this can be seen in Fig.11. In this scenario without Wi-Fi interference, the route 3-2-0 should always be chosen because the distances are such that the total cost for the route 3-2-0 is 2, while the total cost for the route 3-1-0 is 4. Being such, both the LQI and the P-success methods should have always chosen the route 3-2-0. Fig.11 shows that the LQI method chose the best route (3-2-0) most
of the times, more often than the P-success method. This may be due to the fact that \( P_1 \) are being estimated from the link status messages, which occur every 1 second, and may be lost due to random packet loss, or collisions and interference from transmissions from the other nodes. Such losses would cause variance in the estimation of the \( P_1 \) of the link. In contrast, the LQI method estimates the average LQI from every packet transmitted through the link; therefore, it has lower variance than the \( P_1 \) estimation.

4.2 Random-Scenario

A Random-Scenario, shown in the section 3.2.3, was simulated in NS3 by placing the Node 0 at (-80, 0), node 2 at the origin (0, 0) and Node 3 at (80, 0) on the coordinate axes, with no interference. Three other Nodes were placed randomly by the simulator in a circle of radius 80 with center as origin (0, 0). In order to average the randomness of the route discovery procedure and the channel access method, the Random-Scenario was simulated with 30 different seeds for both the methods.
Figure 12: Box Plot of delay in a Random Scenario with 0% Wi-Fi channel time, by using P-success and LQI methods.

Figure 13: Box Plots of ratio of packets sent on the desired route in a Random scenario with 0% Wi-Fi channel time, by using P-success and LQI methods.
Discussion

From Fig.12, it is possible to see that the delay in LQI method and P-success methods are very similar. From Fig.13, it is possible to observe that the LQI method chose the desired route slightly more often than the P-success method for similar reasons as discussed in the Section 4.1.

4.3 Conclusion

From the above simulations, we can conclude that LQI method performs slightly better when compared to the P-success method when there is no Wi-Fi interference because of the lower variance in the estimation procedure.
CHAPTER 5

COMPARISON OF P-SUCCESS AND LQI METHOD WITH VARYING WI-FI INTERFERENCE

This chapter deals with the study and comparison of P-success method and LQI method with varying Wi-Fi interference.

This chapter begins by studying the performance of both methods in two well-controlled scenarios (the T-Scenario and H-Scenario) with nodes in very specific locations. The purpose of studying the two methods in well-controlled scenarios is to better understand how they behave. Later, this thesis compares the performance of both methods in the more realistic Random-Scenario.

5.1 T-Scenario (d2=68m) with Wi-Fi interference

The T-Scenario, shown in the section 3.2.1, was simulated in NS3 by placing the Node 0 at (-80, 0), node 2 at the origin (0, 0), Node 3 at (80, 0) and Node 1 at (0,-68) of the coordinate axes. The Wi-Fi AP was placed at (1, 10), a Wi-Fi client was placed at (-1, 10), and another Wi-Fi client was placed at (0, 20).

In order to average the randomness of the route discovery procedure and the channel access method, the T-Scenario was simulated with 30 different seeds for both the methods.
It is important to observe that, in this T-scenario, the route 3-2-0 is no longer the best route because of the Wi-Fi interference. Notice that the Wi-Fi stations are much closer to node 2 than to node 1. These Wi-Fi nodes cause significant interference in node 2’s transmissions and receptions, meaning that packets originated and received by node 2 have a higher chance of being lost. As a result, the route 3-1-0 is the best route to be chosen in this case.

### 5.1.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time.

![Box Plot of delay in a T-scenario (d2=68) with 37% Wi-Fi channel time, by using P-success and LQI methods.](image)

Figure 14: Box Plot of delay in a T-scenario (d2=68) with 37% Wi-Fi channel time, by using P-success and LQI methods.
Figure 15: Box Plots of ratio of packets sent on desired route in a T-scenario ($d_2=68$) with 37% Wi-Fi channel time, by using P-success and LQI methods.

Discussion

From Fig.14, we see that delay in P-success method is smaller when compared to the LQI method. The reason for larger delay for LQI method is that it chooses the best path (3-1-0) less number of times when compared to P-success method, as seen in Fig.15. The reason for LQI method to choose the path which has maximum interference (3-2-0) is because the LQI based method does not consider lost packets when estimating the average LQI. It only considers packets that were successfully received, which often were transmitted during pauses in the Wi-Fi interference. In contrast, when the interference causes losses in the reception of link status messages, such losses are directly reflected in the probability of successful packet delivery of the P-success method.
5.1.2. Different Wi-Fi Interference Levels

We also repeated these simulations at different levels of Wi-Fi interference and the results are shown in Table 3.

Table 3: Delay to send & receive packets and ratio of packets sent of best route under the two link cost estimation methods with varying Wi-Fi interference in a T-Scenario with $d_2=68m$.

<table>
<thead>
<tr>
<th>Wi-Fi Channel Time (%)</th>
<th>Delay to send &amp; receive packets (in sec)</th>
<th>Ratio of packets sent on best route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
<td>LQI method</td>
</tr>
<tr>
<td>15</td>
<td>0.032</td>
<td>0.033</td>
</tr>
<tr>
<td>26</td>
<td>0.040</td>
<td>0.043</td>
</tr>
<tr>
<td>37</td>
<td>0.115</td>
<td>0.165</td>
</tr>
</tbody>
</table>

Discussion

From Table 3, we can see that the P-success method provides lower delay than the LQI method and the improvement increases as the Wi-Fi interference increases. Also, the best path is chosen more often by P-success method than LQI method. At low interference levels, both methods perform similarly, for the same reasons as discussed in Chapter 4.
5.2 T-Scenario (d$_2$=73m) with Wi-Fi interference

The T-Scenario considered in this section is exactly the same scenario as in section 5.1, except that Node 1 is placed at (0,-73) in this scenario instead of (0,-68). The position of Node 1 was changed to increase the cost of the path 3-1-0 from 4 to 6 and then study the performance of both the methods. As the Wi-Fi stations are in very close proximity to Node 2, the Wi-Fi has significant interference on Node 2 as discussed in the section 5.1. So 3-1-0 still remains the best route even though the cost of the path has been increased.

5.2.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time.

![Figure 16: Box Plot of delay, in a T-scenario (d$_2$=73m) with 37% Wi-Fi channel time, by using P-success and LQI methods.](image-url)
Discussion

From Fig.16, it is possible to see that the P-success method provides smaller delay when compared to the LQI method. The reason for the LQI method for having a larger delay is that it chooses the best path (3-1-0) less number of times when compared to P-success method, as seen in Fig.17. The reason is the same as discussed in the section 5.1.1. In both the methods, the delay is higher and the best path is chosen less often times compared to the scenario in section the 5.1.1, because of the increase in the cost of the best path 3-1-0.

5.2.2 Different Wi-Fi Interference Levels

The comparison between the P-success and LQI methods were repeated at difference levels of Wi-Fi interference and the results are shown in Table 4.
Table 4: Delay to send & receive packets and ratio of packets sent of best route under the two link cost estimation methods with varying Wi-Fi interference in a T-Scenario with $d_z=73m$.

<table>
<thead>
<tr>
<th>Wi-Fi Channel Time (%)</th>
<th>Delay to send &amp; receive packets (in sec)</th>
<th>Ratio of packets sent on best route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
<td>LQI method</td>
</tr>
<tr>
<td>15</td>
<td>0.036</td>
<td>0.037</td>
</tr>
<tr>
<td>26</td>
<td>0.053</td>
<td>0.055</td>
</tr>
<tr>
<td>37</td>
<td>0.220</td>
<td>0.260</td>
</tr>
</tbody>
</table>

**Discussion**

From Table 4, we can see that the P-success method provides lower delay than the LQI method as the Wi-Fi interference increases. Also the best path is chosen more often by the P-success method than the LQI method. In this case, both methods perform similarly because of the higher cost (larger distance of Node 1 from Node 0 and Node 3) of the best path 3-1-0.

**5.3 H-Scenario with Wi-Fi interference**

The H-Scenario, presented in section 3.2.2, was simulated in NS3 by placing the Node 0 at (-80, 0), Node 1 at (0, -68), node 2 at the origin (0, 0), Node 3 at (80, 0), Node 4 at (-80, -80), Node 1 at (80, -80) on the coordinate axes. The Wi-Fi AP was placed at (1, 10), a Wi-Fi client was placed
at (-1, 10), and another Wi-Fi client was placed at (0, 20). In order to average the randomness of the route discovery procedure and the channel access method, the H-Scenario was simulated with 30 different seeds for both the methods.

In the H-scenario without Wi-Fi interference, the route 3-2-0 would be the best route because the distances are such that the total cost for the route 3-2-0 is 2, while the total cost for the route 3-5-1-4-0 is 4. But in this H-scenario with Wi-Fi interference, the route 3-2-0 will no longer be the best route because of the Wi-Fi interference, as discussed in the section 5.1. As a result, the route 3-5-1-4-0 is the best route to be chosen in this case.

5.3.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time.

![Box Plot of delay in a H-scenario with 37% Wi-Fi channel time, by using P-success and LQI methods.](image-url)
Figure 19: Box Plots of ratio of packets sent on the desired route in a H-scenario with 37% Wi-Fi channel time, by using P-success and LQI methods.

Discussion

From Fig.18, it is possible to see that the delay in P-success method is significantly smaller when compared to the LQI method. The reason for larger delay for LQI method is that it chooses the best path (3-5-1-4-0) less often when compared to P-success method, as seen in Fig.19. The reason is same as we discussed in the section 5.1.1.

The delay is smaller in the H-scenario (section 5.3) and the best route is chosen more often when compared to the T-scenario (section 5.1 & section 5.2) in both the methods. This is because the estimations of $P_l$ and average LQI were improved by decreasing the chances of Node 1 and Node 3 losing the RREQ message by adding Node 4 in between Node 0, Node 1 and Node 5 between Node 1 and Node 3.
5.3.2 Different Wi-Fi Interference Levels

These simulations were repeated at difference levels of Wi-Fi interference and the results are shown in Table 5.

Table 5: Delay to send & receive packets and ratio of packets sent of best route under the two link cost estimation methods with varying Wi-Fi interference in a H-Scenario.

<table>
<thead>
<tr>
<th>Wi-Fi Channel Time (%)</th>
<th>Delay to send &amp; receive packets(in sec)</th>
<th>Ratio of packets sent on best route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
<td>LQI method</td>
</tr>
<tr>
<td>15</td>
<td>0.045</td>
<td>0.042</td>
</tr>
<tr>
<td>26</td>
<td>0.048</td>
<td>0.050</td>
</tr>
<tr>
<td>37</td>
<td>0.050</td>
<td>0.140</td>
</tr>
</tbody>
</table>

Discussion

From Table 5, we can see that the P-success method provides lower delay than the LQI method as the Wi-Fi interference increases. Also, P-success method chose the best path more often as the Wi-Fi interference increases. At low interference levels, both methods perform similarly, for the same reasons as discussed in Chapter 4.
5.4 Random-Scenario

The Random-Scenario, presented in the section 3.2.3, was simulated in NS3 by placing the Node 0 at (-80, 0), node 2 at the origin (0, 0), Node 3 at (80, 0) on the coordinate axes. Three other Nodes are placed randomly by the simulator in a circle of radius 80 with center as origin (0, 0). The Wi-Fi AP was placed at (1, 10), a Wi-Fi client was placed at (-1, 10), and another Wi-Fi client was placed at (0, 20). In order to average the randomness of the route discovery procedure and the channel access method, the H-Scenario was simulated with 30 different seeds for both the methods.

In this Random-Scenario, the best path is unknown because of random positions of the remaining three nodes placed randomly by the simulator. Because of this, the only metric used to compare the performance of the two methods is delay.

5.4.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time.
Figure 20: Box Plot of delay in a Random-scenario with 37% Wi-Fi channel time, by using P-success and LQI methods.

Discussion

From Fig.20, it is possible to see that the median delay in the P-success method is slightly smaller when compared to the LQI method. As the best path is unknown, it is not possible to study and compare how often a best path was chosen.

5.4.2 Different Wi-Fi Interference Levels

These simulations were repeated at difference levels of Wi-Fi interference and the results are shown in Table 6.
Table 6: Delay to send & receive packets and ratio of packets sent of best route under the two link cost estimation methods with varying Wi-Fi interference in a Random-Scenario.

<table>
<thead>
<tr>
<th>Wi-Fi Channel time (%)</th>
<th>Delay to send &amp; receive packets (in sec)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
<td>LQI method</td>
</tr>
<tr>
<td>15</td>
<td>0.040</td>
<td>0.037</td>
</tr>
<tr>
<td>26</td>
<td>0.047</td>
<td>0.047</td>
</tr>
<tr>
<td>37</td>
<td>0.190</td>
<td>0.230</td>
</tr>
</tbody>
</table>

Discussion

From Table 6, we can see that the P-success method provides lower median delay than the LQI method as the Wi-Fi interference increases. At low interference levels, both methods perform similarly, for the same reasons as discussed in Chapter 4.

5.5 Conclusion

At lower Wi-Fi interference levels, both the P-Success and the LQI methods seem to perform similarly. As the Wi-Fi interference increases, the P-success method performs better than the LQI method and outperforms it in the presence of high Wi-Fi interference.
CHAPTER 6

INTRODUCTION TO A NEW METHOD (P₁ + LQI) AND ITS COMPARISON WITH P-SUCCESS AND LQI METHODS

6.1 Introduction to the P₁ + LQI Method

From the conclusions discussed in the section 4.3 and section 5.5, it is possible to see that the LQI method performs better in a situation where there is no Wi-Fi interference and the P-success method works better in scenarios with higher Wi-Fi interference. This motivates the idea of combining both P-success and LQI methods and study its performance by comparing it with P-success and LQI method. The goal of this new method is to perform as well as the P-success method in the scenarios that P-success performs better than the LQI method, and perform as well as the LQI method in the scenarios that the LQI method performs better than the P-success method.

The method has two steps:

1. **Estimation of Probability of Transmission Success in a link:** In this first step, nodes use previously received link status messages to estimate the probability of transmission success in the link. This probability of success is then mapped into an integer link cost value between 1 and 7. This step is the same as performed in the P-success method.

2. **Use LQI to differentiate between two paths with the same cost:** In this second step, whenever a node A receives a Route Request message from a node B with the
same cost as a previous Route Request received from a node C, node A computes
the average LQI from past transmissions from node B. If this average LQI is greater
than the average LQI measured from node C’s transmissions, then node A changes
its path to use node B. This step is different from the P-success method because, in
the P-success method, node A would only switch its route to node B if node B’s
Route Request reports a smaller path cost.

Because the method uses first the estimation of probability of success and then the
comparison of average LQIs, this method will be referred to as “P₁+ LQI” method.

It is important to highlight that, in this new method, the node that receives the RREQ
message does not rely solely on the cost reported in the RREQ message. Instead, the receiver of
the RREQ checks the average LQI from the various transmitters in order to differentiate between
two RREQ messages containing the same cost.

For instance, consider the T-Scenario with d₂=60m as shown in section 4.2. Node 2
computes the outgoing cost to Node 0 using the past link status messages, received from node 0.
Node 2 attaches its outgoing cost to Node 0 and rebroadcasts the route request message. When
Node 3 receives route request from Node 2, it computes its outgoing cost to Node 0. Node 3
computes the outgoing cost to Node 2 from the link status messages received from Node 2. The
cumulative outgoing cost for Node 3 to Node 0 is obtained by adding the individual outgoing cost
i.e. outgoing cost of Node 3 to Node 2 and Node 2 to Node 0. The same procedure is followed for
the path 3-1-0.

The problem with existing methods is that path costs have a small granularity; and it may
happen that two paths have the same cost but have different probability of transmission success.
For instance, in the T-scenario of Section 3.2.1, node 3 may receive a Route Request message from both nodes 2 and 1. If no interference is present, the path 3-2-0 is the preferred path; however, because of the granularity of the mapping between probability of transmission success and link cost and because of the variance in estimating probability, the cost of path 3-1-0 may result in the same cost as the path 3-2-0.

If the cost of paths 3-2-0 and 3-1-0 are equal, in the usual methods (P-success, LQI), then either of the two routes will be randomly chosen. Whereas in the new method (P_l + LQI), Node 3 computes its own average LQI received from both the Nodes 1 and 2 to decide between the two; i.e. Node 3 will choose a path which has higher average LQI computed from link status messages and any other received message.

Now, this thesis studies the performance of this method by comparing it with P-success and LQI method with varying interference.

6.2 T-Scenario (d_2=68) with no Wi-Fi Interference

A T-Scenario exactly the same as discussed in the section 4.1 was simulated. The cumulative cost of path 3-2-0 is 2 and cumulative cost of 3-1-0 is 4 so, the best path is 3-2-0 as discussed in the section 4.1. In order to average the randomness of the route discovery procedure and the channel access method, the T-Scenario was simulated with 30 different seeds for all the methods.
Figure 21: Box Plot of delay in a T-scenario (d₂=68m) with 0% Wi-Fi channel time, by using P-success, LQI, Pl + LQI methods.

Figure 22: Box Plots of ratio of packets sent on the desired route in a T-scenario (d₂=68m) with 0% Wi-Fi channel time, by using P-success, LQI, Pl + LQI methods.
Discussion

From Fig. 21, it is possible to see that the delay is very similar to that in the P-success method and higher than that in the LQI method. From Fig. 22, it is possible to see that the best path was chosen similarly in both Pτ + LQI method and LQI method because, Node 3 in this scenario doesn’t have paths with the same cumulative cost. So, as desired, the Pτ + LQI method performs similarly to the LQI method as discussed in the section 6.1.

6.3 T-Scenario (d2=60) with no Wi-Fi Interference

To better study the performance of Pτ + LQI method, d2 has been changed to 60m in the T-Scenario, still with no Wi-Fi inference. In order to average the randomness of the route discovery procedure and the channel access method, the T-Scenario was simulated with 30 different seeds for both the methods.

As d2 has been decreased to 60m, the cumulative cost of path 3-2-0 and 3-1-0 will be 2 in both cases. It is important to observe that path 3-1-0 has same cost as path 3-2-0 because of the low granularity of the mapping between probability of successful packet delivery and the link cost. More precisely, the actual probability of successful packet delivery through path 3-1-0 is lower than through path 3-2-0; however, both map into the same cost 2. Thus, in here, Node 3 will have two paths with equal cost. So, in both the P-Success and LQI-based methods, node 3 will choose between the best path (3-2-0) and the other path (3-1-0) randomly. In contrast, in the Pτ + LQI method, the method chooses the link (3-2-0) because node 3 measures node 2’s transmissions with higher average LQI.
Figure 23: Box Plot of delay in a T-scenario (d₂=60m) with 0% Wi-Fi channel time, by using P-success, LQI, P_l + LQI methods.

Figure 24: Box Plots of ratio of packets sent on the desired route in a T-scenario (d₂=60m) with 0% Wi-Fi channel time, by using P-success, LQI, P_l + LQI methods.
Discussion

From Fig. 23, it is possible to see that the delay of the $P_1 + LQI$ method is smaller than that in both $P$-success and LQI methods. Both the methods $P$-success and LQI methods choose either of the paths 3-2-0 or 3-1-0 randomly because they have the same cumulative cost. In contrast, as shown in Fig. 24, the method $P_1 + LQI$ chooses the path 3-2-0 more often because of its higher average LQI. The path 3-2-0 has higher average LQI than the path 3-1-0 because Node 2 was placed closer to Node 3 than node 1.

6.4 T-Scenario ($d_2=68$) with Wi-Fi Interference

A T-Scenario exactly the same as discussed in the section 5.1 was simulated. The best path will be 3-1-0 as discussed in the section 5.1. The cumulative cost of the path 3-2-0 is higher than that of 3-1-0 because of higher Wi-Fi interference for Node 2 as discussed in the section 5.1. In order to average the randomness of the route discovery procedure and the channel access method, the T-Scenario was simulated with 30 different seeds for both the methods.

6.4.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time.
Figure 25: Box Plot of delay in a T-scenario \((d_2=68m)\) with 37\% Wi-Fi channel time, by using P-success, LQI, Pl + LQI methods.

Figure 26: Box Plots of ratio of packets sent on the desired route, in a T-scenario \((d_2=68m)\) with 37\% Wi-Fi channel time, by using P-success, LQI, Pl + LQI methods.
Discussion

From Fig.25 and Fig.26, it is possible to see that, as desired, both $P_{l}+LQI$ and P-success methods have performance very similar to each other. As the cumulative cost of the paths available to Node 3 are different, as discussed in the section 6.4, the $P_{l}+LQI$ method performs similarly as P-success method. The $P_{l}+LQI$ method performs as expected, discussed in the section 6.1.

6.4.2 Different Wi-Fi Interference Levels

These simulations were repeated at difference levels of Wi-Fi interference and the results are shown in Table 7.

<table>
<thead>
<tr>
<th>Wi-Fi Channel Time (%)</th>
<th>Delay to send &amp; receive packets (in sec)</th>
<th>Ratio of packets sent on best route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
<td>LQI method</td>
</tr>
<tr>
<td>15</td>
<td>0.032</td>
<td>0.033</td>
</tr>
<tr>
<td>26</td>
<td>0.040</td>
<td>0.043</td>
</tr>
<tr>
<td>37</td>
<td>0.115</td>
<td>0.165</td>
</tr>
</tbody>
</table>

Table 7: Delay to send & receive packets and ratio of packets sent of best route under the three link cost estimation methods with varying Wi-Fi interference in a T-Scenario with $d_{2}=68$. 
Discussion

With varying Wi-Fi interference, it is possible to see from Table 7 that both the P-success and P1+ LQI methods perform similarly, as desired.

6.5 T-Scenario (d_2=73) with Wi-Fi Interference

A T-Scenario exactly the same as discussed in the section 5.2 was simulated. The best path is 3-1-0 as discussed in the section 5.2. The cumulative cost of the path 3-2-0 still remains higher than 3-1-0. In order to average the randomness of the route discovery procedure and the channel access method, the T-Scenario was simulated with 30 different seeds for both the methods.

6.5.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time.
Figure 27: Box Plot of delay in a T-scenario (d₂=73m) with 37% Wi-Fi channel time, by using P-success, LQI, P₁ + LQI methods.

Figure 28: Box Plots of ratio of packets sent on the desired route, in a T-scenario (d₂=68m) with 37% Wi-Fi channel time, by using P-success, LQI, P₁ + LQI methods.
Discussion

From Fig.27 and Fig.28, it is possible to see that both P₁+LQI and P-success methods have performed similarly to each other, as desired. The reason is same as we discussed in the section 6.4.1.

6.5.2 Different Wi-Fi Interference Levels

These simulations were repeated at difference levels of Wi-Fi interference and the results are shown in Table 8.

Table 8: Delay to send & receive packets and ratio of packets sent of best route under the three link cost estimation methods with varying Wi-Fi interference in a T-Scenario with d₂=73m.

<table>
<thead>
<tr>
<th>Wi-Fi Channel Time (%)</th>
<th>Delay to send &amp; receive packets(in sec)</th>
<th>Ratio of packets sent on best route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
<td>LQI method</td>
</tr>
<tr>
<td>15</td>
<td>0.036</td>
<td>0.037</td>
</tr>
<tr>
<td>26</td>
<td>0.053</td>
<td>0.055</td>
</tr>
<tr>
<td>37</td>
<td>0.220</td>
<td>0.260</td>
</tr>
</tbody>
</table>
Discussion

Even with varying Wi-Fi interference, it is possible to see from Table 8 that both the P-success and P\textsubscript{L}+ LQI methods perform similarly, as desired. The similar performance of both the P\textsubscript{L} +LQI and P-success methods has also been seen in the scenario discussed in the section 6.4.

6.6 H-Scenario with Wi-Fi Interference

Now, the H-Scenario exactly the same as discussed in the section 5.3 was simulated. The best path is 3-5-1-4-0, as discussed in the section 5.3. A higher Wi-Fi interference for Node 2 makes the cumulative cost of the path 3-2-0 higher than the cumulative cost of the path 3-5-1-4-0. In order to average the randomness of the route discovery procedure and the channel access method, the H-Scenario was simulated with 30 different seeds for both the methods.

6.6.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time.
Figure 29: Box Plot of Delay in a T-scenario with 37% Wi-Fi channel time, by using P-success, LQI, P_l + LQI methods.

Figure 30: Box Plots of Ratio of packets sent on the desired route, in a H-scenario with 37% Wi-Fi channel time, by using P-success, LQI, P_l + LQI methods.
Discussion

From Fig.29 and Fig.30, it is possible to see that the performance of both the \( P_t \) +LQI and P-success methods are similar. The reason is very similar to that discussed in T-Scenarios in sections 6.5.1 and 6.5.2. The costs of the paths 3-5-1-4-0 and 3-2-0 are different so, the \( P_t \) +LQI method performs as desired; i.e. similar to P-success method as discussed in the section 6.1.

6.6.2 Different Wi-Fi Interference Levels

These simulations were also repeated at difference levels of Wi-Fi interference and the results are shown in Table 9.

Table 9: Delay to send & receive packets and ratio of packets sent of best route under the three link cost estimation methods with varying Wi-Fi interference in a H-Scenario.

<table>
<thead>
<tr>
<th>Wi-Fi Channel Time (%)</th>
<th>Delay to send &amp; receive packets (in sec)</th>
<th>Ratio of packets sent on best route</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
<td>LQI method</td>
</tr>
<tr>
<td>15</td>
<td>0.045</td>
<td>0.042</td>
</tr>
<tr>
<td>26</td>
<td>0.048</td>
<td>0.050</td>
</tr>
<tr>
<td>37</td>
<td>0.050</td>
<td>0.140</td>
</tr>
</tbody>
</table>
Discussion

Even with varying Wi-Fi interference, it is possible to see from Table 9 that, both the P-success and $P_1 + \text{LQI}$ methods perform similarly, as desired. The similar performance of both $P_1 + \text{LQI}$ and P-success methods has also been seen in the scenario discussed in the sections 6.4 and 6.5.

6.7 Random-Scenario with Wi-Fi Interference

A Random-Scenario, exactly the same as we discussed in the section 5.4, has been simulated to evaluate the performance of the $P_1 + \text{LQI}$ method and compare against the P-success and LQI methods. The best path is unknown so, delay is only the metric used to evaluate the performance of the methods as discussed in the section 5.4.

6.7.1 Wi-Fi interference- Wi-Fi occupying 37% of the channel time

Consider first the case in which the Wi-Fi nodes generate traffic that consume an average of 37% of the channel time. In order to average the randomness of the route discovery procedure and the channel access method, the Random-Scenario was simulated with 100 different seeds for both the methods.
Discussion

From Fig.31, it is possible to see that the $P_1 + LQI$ method performed similarly to the $P$-success and LQI methods, as desired.

6.7.2 Different Wi-Fi Interference Levels

These simulations were also performed at different levels of Wi-Fi interference and the results are shown in Table 10.
Table 10: Delay to send & receive packets under different link cost estimation methods with varying Wi-Fi interference in a Random-Scenario.

<table>
<thead>
<tr>
<th>Wi-Fi Channel Time (%)</th>
<th>Delay to send &amp; receive packets (in sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-success method</td>
</tr>
<tr>
<td>15</td>
<td>0.040</td>
</tr>
<tr>
<td>26</td>
<td>0.047</td>
</tr>
<tr>
<td>37</td>
<td>0.190</td>
</tr>
</tbody>
</table>

Discussion

From Table 10, we see that both the P₁ +LQI and P-success methods perform very similarly, as desired. This similar performance has been observed in the T-Scenario and the H-Scenario as well i.e. sections 6.4, 6.5 and 6.6.

6.8 Conclusion

After evaluating the performance of the P₁ +LQI method in different scenarios and comparing it against the P-success and LQI methods, it is possible to conclude that the P₁ +LQI method performs as desired: it performs as well as the LQI-based method in scenarios without Wi-Fi interference; and it performs as well as the P-success method in scenarios with Wi-Fi
interference. In fact, because it uses local information about LQI measurements to decide between routes with equal costs, the P\textsubscript{1} + LQI method can perform better than both the P-success and LQI methods in scenarios where a source node has multiple paths with the same cumulative cost.

In random scenarios, the P\textsubscript{1} + LQI method has similar performance as the P-success and LQI methods, illustrating that the P\textsubscript{1} + LQI method is not harming the route selection in these scenarios while improving the performance in other scenarios, such as the T-scenario and the H-scenario.
The P-success method is a link cost estimating method used in ZigBee wireless networks in which costs are determined by estimating the probability of successful packet delivery in the link. An alternative method used by some manufacturers [12] is the LQI method. This method maps the SINR measurements into an 8 bit number called LQI (Link Quality Indicator) and nodes estimate link costs from various LQI measurements.

If there is no Wi-Fi interference, both the P-success and LQI methods perform very similarly. But, the LQI method has a slight advantage because, in the P-success method, the probability of successful packet delivery ($P_l$) is estimated from the link status messages, which have a limited transmission rate and may be lost due to random packet loss, or collisions and interference from transmissions from the other nodes. Such losses would cause variance in the estimation of the $P_l$ of the link. In contrast, the LQI method estimates the average LQI from every packet transmitted through the link; therefore, it has lower variance than the $P_l$ estimation.

In the presence of Wi-Fi interference, P-success method performs better than the LQI method as, it chooses the best route more often when compared to LQI method. This is because the LQI-based method does not consider lost packets when estimating the average LQI. It only considers packets that were successfully received, which often were transmitted during pauses in the Wi-Fi interference. In contrast, when the interference causes losses in the reception of link
status messages, such losses are directly reflected in the probability of successful packet delivery of the P-success method.

The problem with the LQI method is that it tries to \textit{indirectly} estimate the true cost, which is the true probability of successful transmission in a link, by estimating it with the LQI in received packets. The problem is that the LQI in successfully received packets do not carry information about packets that were lost.

In order to obtain the benefits of both methods, this thesis proposes the combination of the two approaches in a new method. This new method ($P_1 + \text{LQI}$) performs similarly as the P-Success method in scenarios with Wi-Fi interference, and perform similarly, or better, than the LQI-based method in scenarios without Wi-Fi interference.
Bibliography


