IMPROVE THE ACCURACY RATE OF LINK QUALITY ESTIMATION USING FUZZY LOGIC IN MOBILE WIRELESS SENSOR NETWORKS

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ABSTRACT

Link quality estimation is essential for improving the performance of a routing protocol in Wireless Sensor Networks. Many methods have been proposed to increase the performance of the link quality estimation, however, most of them are not able to evaluate link quality accurately. In this study, a method that uses fuzzy logic to evaluate both hardware-based and software-based metrics is proposed to improve the accuracy rate for evaluating a link quality. This proposed method consists of three types of modules, the Fuzzifier module, the Inference module, and the Defuzzifier module. The Fuzzifier module is used to determine the degree to which input link quality metrics belong to each fuzzy set using proposed membership functions. The Inference module obtains the rule outputs based on the proposed fuzzy rules and the given inputs acquired from the Fuzzifier module. The Defuzzifier module is used to aggregate the rule outputs inferred from the Inference module. The result from the Defuzzifier module is then used to evaluate the link quality. A simulation was conducted to evaluate the accuracy rates of the proposed method and those found in the other related works. The results showed that the proposed method had a higher accuracy rate than the other related works for evaluating a link quality.

Keywords: Wireless Sensor Networks, Link Quality Estimation, Fuzzy Logic.

ABSTRAK

Anggaran kualiti link adalah penting untuk meningkatkan prestasi protokol laluan dalam Rangkaian Sensor Tanpa Wayar. Banyak kaedah telah dicadangkan untuk meningkatkan prestasi anggaran kualiti link. Walau bagaimanapun, kebanyakan kaedah ini tidak dapat menilai kualiti link dengan tepat. Dalam kajian ini, satu kaedah yang menggunakan logik kabur untuk menilai metrik yang berasaskan perkakasan dan perisian dicadangkan untuk meningkatkan kadar ketepatan dalam penilaian kualiti link. Kaedah yang dicadangkan ini terdiri daripada tiga jenis modul, iaitu modul Fuzzifier, modul Inference dan modul Defuzzifier. Modul Fuzzifier digunakan untuk menukar input metrik kualiti link ke set kabur masing-masing dengan menggunakan beberapa fungsi keahlian yang dicadangkan. Modul Inference mendapat aturan output berdasarkan aturan kabur yang dicadangkan dan input diberikan dari modul Fuzzifier. Modul Defuzzier digunakan untuk mengagregat aturan output yang disimpulkan dari modul Inference. Keputusan yang diperolehi dari modul Defuzzifier kemudian digunakan untuk menilai kualiti link. Satu simulasi teleh dijalankan untuk menilai kadar ketepatan bagi kaedah yang dicadangkan dan kerja-kerja lain yang berkaitan. Keputusan simulasi telah menunjukkan bahawa kaedah yang dicadangkan mempunyai kadar ketepatan yang lebih tinggi daripada kerja-kerja lain yang berkaitan dalam penilaian kualiti link.

Keywords: Rangkaian Sensor Tanpa Wayar, Anggaran Kualiti Pautan, Logik Fuzzy.

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LIST OF SYMBOLS AND ABBREVIATIONS

CSI	:	Channel State Information
E2E-DDR	:	End-to-End Data Delivery Reliability
EWMA	:	Exponentially Weighted Moving Average
F-LQE	:	Fuzzy Link Quality Estimator
LQE-node	:	Link Quality Estimation node
LQI	:	link quality indicator
Opt-FLQE	:	Optimized Fuzzy Link Quality Estimator
PRR	:	Packet Reception Ratio
RSSI	:	received signal strength indicator
SNR	:	signal to noise ratio
WSN	:	Wireless Sensor Network
WMEWMA	:	Window Mean with Exponentially Weighted Moving Average

CHAPTER 1: INTRODUCTION

1.1 Background

A Wireless Sensor Network (WSN) is a wireless network that is composed of a group of spatially dispersed sensor nodes with a radio transceiver (Liu & Zhao, 2018). These sensor nodes are used to monitor the physical conditions of the environment and transmit the collected data to a sink (Lin *et al.*, 2016). WSN is widely applied in many sectors such as military, industry and environmental monitoring (Li *et al.*, 2018; Soleymani *et al.*, 2017). WSN relies on the sensor nodes to transmit packets. These sensor nodes normally have limited power supply due to their size and their transmission rates are affected by many factors (Abdul-Salaam, Abdullah, & Anisi, 2017; Qu, Lei, Tang, & Wang, 2018)

Link quality is a significant factor that affects the transmission rate of sensor nodes, and link quality metrics are used to evaluate a link quality (Baccour *et al.*, 2012; Lowrance & Lauf, 2017). There are two types of link quality metrics – hardware-based and software-based (Lowrance & Lauf, 2017). Hardware-based metrics are acquired directly from radio transceivers such as Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI) and Signal to Noise Ratio (SNR). Software-based metrics are attained through a calculation that is in accordance with the received packet statistics such as Packet Reception Ratio (PRR). Different types of link quality metrics have different characteristics. For example, hardware-based metrics evaluations can reflect the changes of the link quality in real time (Shu, Liu, Liu, Zhan, & Hu, 2017). Software-based metrics can evaluate the link quality more accurately than hardware-based metrics (Aswale & Ghorpade, 2018). However, using only software-based metrics to evaluate a link quality cannot reflect the changes of the link quality in real time (Baccour *et al.*, 2012). Therefore, proposing a method to improve the link quality estimation is crucial.

1.2 Statement of the problem

Several link quality estimation methods have been proposed over the years. According to (Woo *et al.,* 2003), the Exponentially Weighted Moving Average (EWMA) filter was employed in their study to calculate Packet Reception Ratio (PRR) to avoid the fluctuation of PRR. In the study of Puccinelli *et al.*, the normalising of Received Signal Strength Indicator (RSSI) and Link Quality Indicator (LQI) was used to evaluate a link quality (Puccinelli *et al.,* 2008). Further, in the study of Qin *et al*., the Kalman filter was utilised to combine Signal to Noise Ratio (SNR) and LQI to evaluate a link quality (Qin *et al*., 2013). However, these methods have low accuracy rates for link quality evaluations because they use the same type of link quality metrics to evaluate a link quality (Aswale & Ghorpade, 2018). There are several drawbacks to using only hardware-based or software-based metrics. For example, the packet lost information might not be considered when evaluating a link quality by just using hardware-based metrics. On the other hand, the changes of the link quality in real time are not reflected when evaluating a link quality with methods that only consider software-based metrics (Baccour *et al.*, 2012).

To improve link quality estimation, Aswale *et al.* used the Pythagorean theorem to evaluate both hardware-based and software-based metrics (Aswale *et al.*, 2018). This method has yielded a higher accuracy rate for evaluating the link quality compared to other methods that only use the same type of link quality metrics. However, it is difficult to distinguish the link quality around the thresholds by using the Pythagorean theorem because the link quality metrics are imprecise and lead to a subsequent decrease in the accuracy rate. In light of the above-described shortcomings, this study aims to fill this gap by using fuzzy logic to improve the accuracy rate for evaluating a link quality.

1.3 Statement of objectives

The objectives of this study are stated as below:

a. To propose a method to improve the accuracy rate for evaluating a link quality.
b. To develop the proposed method using fuzzy logic to evaluate both hardware-based and software-based metrics.
c. To compare the accuracy rate of the proposed method with other methods introduced in related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI methods).

1.4 Scope of the research

This study focuses on proposing a method that uses fuzzy logic to improve the accuracy rate for evaluating a link quality at receiver nodes. The proposed method is tested by using a simulator. The accuracy rate of this proposed method is then compared with those of the Triangle Metric method, WMEWMA method, improved-LQI method, effective-SNR method, LQE-node method, and CSI method.

1.5 Significance of the research

A method that uses fuzzy logic to evaluate both hardware-based and software-based metrics is proposed to improve the accuracy rate when evaluating a link quality. It is speculated that the proposed method could have a higher accuracy rate for evaluating a link quality when compared to other related works.

1.6 Organisation of the dissertation

The organisation of the dissertation is detailed below.

Chapter 1 introduces the background of this research, including the technologies that have triggered it, the problem statement, the statement of objectives, the research scope and the significance of the study.

Chapter 2 presents the literature review of previous research in this area, including the types of link quality estimation methods that have been proposed, selected related works, and summaries of their respective strengths and shortcomings.

Chapter 3 introduces the methodology of this study. The various stages which make up the research methodology framework, comprised of the Information Gathering and Analysis stage, the Proposed Method stage, the System Design and Implementation stage, the Testing and Evaluation stage and the Documentation stage, are explained.

Chapter 4 presents the design and implementation of the proposed method, which consists of the link quality metrics, the architecture of the proposed method and the details of the modules use.

Chapter 5 discusses the testing and analysis stage of the proposed system, that is, the simulation setup and the evaluation of the proposed method.

Chapter 6 presents the conclusions of this study, detailing the achievement of the objectives, this study's contributions to the field and future directions for further research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter begins with a discussion of the concept of fuzzy logic and an overview of types of link quality estimation methods. They are followed by a discussion of selected related works and their strengths and shortcomings.

2.2 The concept of fuzzy logic

In classical logic theory, there are only two options (either 0 or 1), where the metric either belongs to or does not belong to the set. By using a fuzzy logic approach, the parameter range can be extended. Any value within the range of 0 to 1 can be used as an indicator for the degree to which the metric belongs to the fuzzy set. Fuzzy logic provides a rigorous algebra for dealing with imprecise information. Fuzzy logic establishes the approximate truth value of propositions based on linguistic variables and inference rules (Baccour *et al.*, 2015). A fuzzy set is defined as a class of objects with a continuum of grades of membership. Formally, a fuzzy set A of a universe of discourse $X = \{x\}$ is defined as $A = \{x; \mu A(x) \mid \forall\, x \in X\}$, where X is a space of points and $\mu A(x)$ is a membership function of $x \in X$ being an element of A.

2.3 Types of link quality estimation methods

According to (Lowrance & Lauf, 2017), link quality estimation methods can be categorised into three categories — hardware-based, software-based and hybrid methods, as reflected in Figure 2.1 below.

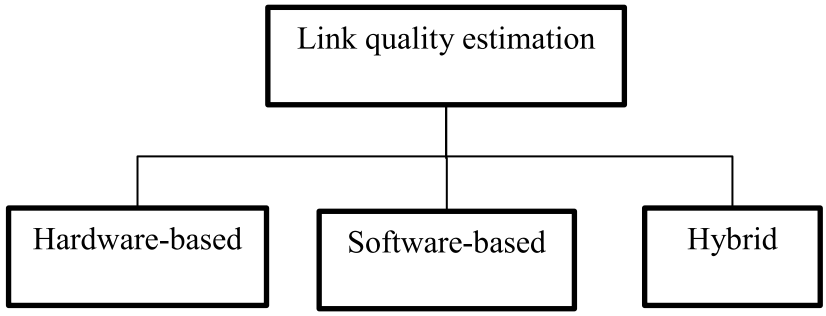


Figure 2.1: Classification of link quality estimation methods (adapted from Lowrance & Lauf, 2017)

Hardware-based link quality estimations are known as physical layer link quality estimations (Lowrance & Lauf, 2017). Previously, researchers normalised hardware-based metrics such as RSSI and LQI to evaluate a link quality (Puccinelli & Haenggi, 2008). After that, other researchers used the Kalman filter to combine other hardware-based metrics such as SNR and LQI to evaluate a link quality (Qin *et al.*, 2013). These hardware-based metrics are obtained directly from the radio transceiver. Therefore, these methods have lower overheads and are more sensitive to changes of the link quality compared to software-based link quality estimations. However, hardware-based link quality estimations are device-dependent, and they have a lower accuracy rate than software-based ones (Baccour, Koubâa, Youssef, & Alves, 2015).

Software-based link quality estimations are also known as data link layer link quality estimations (Lowrance & Lauf, 2017). One such method is by way of using an EWMA filter to calculate Packet Reception Ratio (PRR) (Woo *et al.*, 2003). This method uses software-based metrics to evaluate a link quality by calculating the received packets or sent packets. According to the authors, these software-based link quality estimations have higher accuracy rates compared to hardware-based link ones because the former are device independent (Baccour *et al.*, 2015). However, software-based link quality estimations are complex, and they have higher overheads compared to hardware-based link quality estimations (Baccour *et al.*, 2015).

Hybrid link quality estimations are known as cross-layer link quality estimations (Lowrance & Lauf, 2017). These methods evaluate a link quality based on both hardware-based and software-based metrics. In the previous study (Zuniga *et al.*, 2011), hardware-based metrics (RSSI and LQI) and software-based metrics (PRR) were used to choose the best link. Recently, Aswale *et al.* used the Pythagorean theorem to combine hardware-based metrics (SNR and LQI) and software-based metrics (PRR) to evaluate link quality (Aswale *et al.*, 2018). Those studies showed that hybrid link quality estimations have higher accuracy rates compared to hardware-based and software-based link quality estimations. However, these hybrid link quality estimations need additional computation resources. The following section discusses these related works in more detail.

2.4 Related works

A significant number of link quality estimation methods have been developed over the years. However, most of the current link quality estimation methods display low accuracy rates for evaluating link quality (Aswale & Ghorpade, 2018; Zuniga *et al.*, 2011). It is challenging to distinguish the link quality around thresholds as the link quality metrics are usually imprecisely estimated (Baccour *et al.*, 2015). Because nodes move randomly in mobile wireless sensor networks, the environment is unpredictable and dynamic (Lowrance & Lauf, 2017). Therefore, link quality evaluation in mobile wireless sensor networks is more difficult than in static wireless sensor networks. Here, several selected link quality estimation methods are analysed in terms of their strengths and shortcomings, including Window Mean with Exponentially Weighted Moving

Average (WMEWMA) Channel State Information (CSI), Triangle Metric, effective-Signal to Noise Ratio (SNR), improved-Link Quality Indicator (LQI), Fuzzy-Link Quality Estimator (F-LQE), Optimised-Fuzzy Link Quality Estimator (Opt-FLQE), Link Quality Estimation node (LQE-node) and End-to-End Data Delivery Reliability (E2E-DDR).

Window Mean with Exponentially Weighted Moving Average (WMEWMA) is a link quality estimation method that was proposed by (Woo *et al.*, 2003). In this method, PRR is computed according to link measurements, and where this computed PRR is filtered using the Exponentially Weighted Moving Average (EWMA) filter to avoid transient fluctuation of PRR. However, WMEWMA is not able to evaluate a link quality accurately because it cannot account for the change of link quality quickly enough.

Channel State Information (CSI) was proposed by Puccinelli *et al.* in the year 2008 (Puccinelli *et al.*, 2008). Two hardware-based metrics, RSSI and LQI, are used in this method to evaluate a link quality because RSSI can show good links, and LQI can indicate bad links. The RSSI and LQI are normalised after extraction from transceivers. The normalised RSSI and LQI are then combined with the evaluated link quality for further calculation. Although CSI is simple and easy to calculate, the evaluation of a link quality is not accurate because hardware-based metrics do not consider packet lost information.

Boano *et al.* suggested the Triangle Metric method to evaluate link quality in mobile wireless sensor network (Boano *et al.*, 2010). This method uses hardware-based metrics (LQI and SNR), and the packet lost information is included when evaluating a link quality. The LQI and SNR are acquired from the transceiver in each receiver node. The mean values of the LQI and SNR are calculated based on the number of packets from the receiver node and the sender node. The Pythagorean theorem is then used to combine the mean values of the LQI and SNR to evaluate a link quality. The worth of this method, which considers both received packets and packets lost information, is that it can evaluate a link quality more accurately when compared to others that use only the same type of link quality metrics. However, its shortcoming is that the link quality metrics might not be able to be estimated precisely because the link quality around thresholds is not distinguished.

Effective-Signal to Noise Ratio (SNR) is a link quality estimation method proposed by (Qin *et al.,* 2013). The Kalman filter was used to combine SNR and LQI to obtain the Effective-SNR value for evaluating a link quality. This method is able to reduce overhead problems. However, it cannot evaluate a link quality accurately because it uses only hardware-based metrics and does not consider packet lost information.

Improved-Link Quality Indicator (LQI) was suggested by Chen *et al.* in 2014 (Chen *et al.*, 2014). The LQI values of both successful and non-successful received packets are used to calculate the mean values of overall LQI. This method is able to improve the accuracy and efficiency of evaluating a link quality when compared to a method that only considers the successfully received packets in calculating the mean values of the LQI. However, it needs additional resources to calculate LQI values of non-successful received packets. Furthermore, the improved-LQI cannot evaluate a link quality between two mobile nodes accurately because it does not consider the situation when mobile nodes are not inside the transmission range of the other party.

In 2015, Baccour *et al.* proposed a Fuzzy Link Quality Estimator (F-LQE) method (Baccour *et al.*, 2015). According to authors, this method can be used to estimate link quality in both static wireless sensor network and mobile wireless sensor network. This method uses fuzzy logic to combine four factors that are related to link quality — packet delivery, stability, asymmetry, and channel quality. A software-based metric, PRR, is the elementary metric used to calculate the packet delivery, stability, and asymmetry while channel quality is represented by SNR, a hardware-based metric. F-LQE can improve the end-to-end packet delivery and topology stability, and at the same time, reduce the number of packet retransmissions and the hop count. However, F-LQE can only be used to determine the good link quality. Moreover, F-LQE may become unreliable because it cannot react quickly to the change of link quality when the link is in a harsh environment or under a mobile wireless sensor network. Thus, F-LQE method cannot evaluate a link quality accurately.

Optimised Fuzzy Link Quality Estimator (Opt-FLQE) has been recommended for evaluation of the extremely unreliable link by replacing the stability with the packet retransmission (Rekik, Baccour, Jmaiel, & Drira, 2016). This method also uses fuzzy logic to combine four factors that are related to link quality, namely packet delivery, packet retransmission, asymmetry, and channel quality. Thus this method can overcome problems that are imposed by link unreliability. However, this method cannot evaluate a link quality accurately because it can only be used to determine the good link quality.

A dedicated node — Link Quality Estimation node (LQE-node) was proposed by Gomes *et al.* to evaluate link quality in 2017 (Gomes *et al.* 2017). This LQE-node uses a hardware-based metrics (RSSI) to evaluate a link quality with the consideration of the influence and interference in multipath. The sensor nodes do not need to send broadcast probe packets or stop their operation to monitor link quality. However, this method is not able to evaluate a link quality accurately because hardware-based metrics do not consider packet lost information.

End-to-End Data Delivery Reliability (E2E-DDR) uses four metrics, which are the distance between nodes, the background noise, the environmental conditions, and the hardware states, to evaluate link quality (Sun *et al.*, 2018). This method was proposed by Sun *et al.* in 2018. It can evaluate the link quality accurately in a static wireless sensor network. However, the nodes in the mobile wireless sensor network are movable, and the distances between mobile nodes are difficult to measure. Because of this, E2E-DDR is not able to evaluate a link quality accurately in the mobile wireless sensor network.

The strengths and weaknesses of each of the selected link quality estimation methods are summarised in the Table 2.1.

Table 2.1: Comparison of selected link quality estimation methods

Method	Year	Advantages	Drawbacks
WMEWMA	2003	• Able to avoid transient fluctuation of PRR.	• Unable to evaluate a link quality accurately because it cannot account for the change of link quality quickly enough.
CSI	2008	• Simple and easy to calculate.	• Not accurate because hardware-based metrics do not consider packet lost information.
Triangle Metric	2010	• Can evaluate a link quality more accurately when compared to others that use only the same type of link quality metrics.	• Not be able to be estimated precisely because the link quality around thresholds is not distinguished.
Effective-SNR	2013	• Reduces overhead problems.	• Cannot evaluate a link quality accurately because it uses only hardware-based metrics and does not consider packet lost information.
improved-LQI	2014	• Improves the accuracy and efficiency of evaluating a link quality when compared to the methods that only consider the successfully received packets in calculating the mean values of the LQI.	• Need additional resources. • Cannot evaluate a link quality between two mobile nodes accurately because it does not consider the situation when mobile nodes are not inside the transmission range of the other party.
F-LQE	2015	• Improves the end-to-end packet delivery and the topology stability. • Reduces the number of packet retransmissions and the hop count.	• May become unreliable because it cannot react quickly to the change of link quality when the link is in a harsh environment or under a mobile wireless sensor network • Cannot evaluate a link quality accurately.
Opt-FLQE	2016	• Overcomes problems that imposed are by link unreliability.	• Cannot evaluate a link quality accurately because it can only determine the good link quality.
LQE-node	2017	• The sensor nodes do not need to send broadcast probe packets or stop their operation to monitor link quality.	• Not able to evaluate a link quality accurately because hardware-based metrics do not consider packet lost information.
E2E-DDR	2018	• Evaluates the link quality accurately in a static wireless sensor network	• Not able to evaluate a link quality accurately in the mobile wireless sensor network.

2.5 Chapter Summary

This chapter reviewed previous literature relevant to the study. Several link quality estimation methods were analysed in terms of their strengths and shortcomings. Most of the link quality estimation methods were not able to evaluate a link quality accurately because these methods could not account for the change of link quality quickly enough. Some of the methods only used hardware-based metrics to evaluate a link quality and did not consider the packet lost information. Therefore, the link quality around thresholds could not be distinguished. Other methods had been proposed to increase the accuracy rate when evaluating a link quality but they were only suitable for implementation in static wireless sensor networks, and thus could not evaluate link quality accurately in mobile wireless sensor networks. To fill this gap in the research, this study is conducted to improve the accuracy rate for evaluating a link quality in mobile wireless sensor networks.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This chapter presents the methodology used in this study. The various stages that make up the research methodology framework are explained. The stages are: the Information Gathering and Analysis stage, the Proposed Method stage, the System Design and Implementation stage, the Testing and Evaluation stage, and the Documentation stage.

3.2 Research methodology

There are five stages involved in this study: Information Gathering and Analysis, Proposed Method, System Design and Implementation, Testing and Evaluation, and Documentation. How the stages fit together to constitute the research methodology are shown in Figure 3.1.

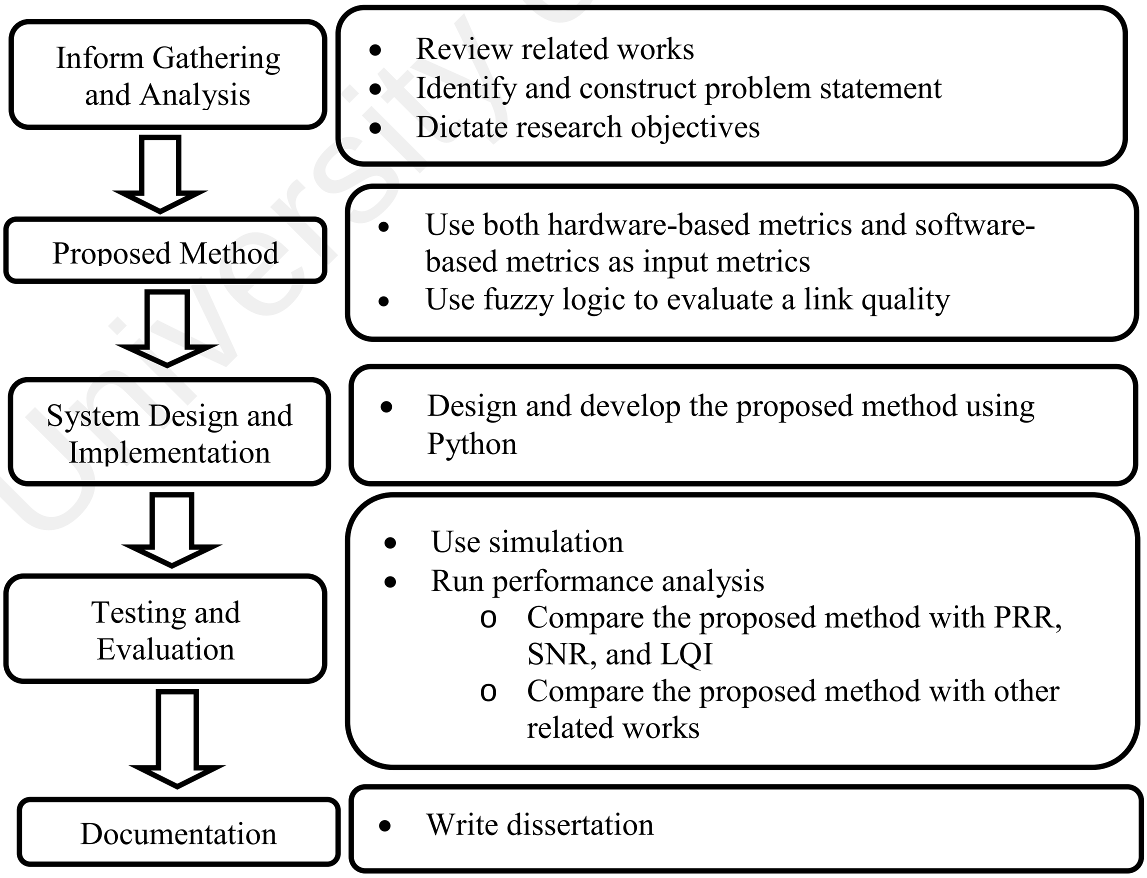


Figure 3.1: Research methodology framework

3.3 Information gathering and analysis

Previous research considered to be related to this study was gathered from various sources such as journal articles, conferences, and websites. Methods contained in such related works were analysed in terms of their advantages and disadvantages. From this analysis, the problem statement of low accuracy rate when evaluating a link quality was identified. To address the problem, three objectives were established:

a. To propose a method to improve the accuracy rate for evaluating a link quality.
b. To develop the proposed method using fuzzy logic to evaluate both hardware-based and software-based metrics.
c. To compare the accuracy rate of the proposed method with other methods introduced in related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI methods).

3.4 Proposed method

To achieve the first objective, a method that uses fuzzy logic to evaluate the hardware-based and software-based metrics was proposed to improve the accuracy rate for evaluating a link quality. This proposed method consists of three types of modules: the Fuzzifier module, the Inference module, and the Defuzzifier module. The Fuzzifier module is used to convert the input link quality metrics to their respective fuzzy sets based on several proposed membership functions. The Inference module is used to imitate the inference process of a human. It obtains the rule output based on the proposed fuzzy rules and the given input acquired from the Fuzzifier module. The proposed fuzzy rule is translated to the equation using "and-like" and "or-like" operators for the rule output calculation. The Defuzzifier module is used to aggregate the rule outputs that are inferred from the Inference module. The result obtained from the Defuzzifier module is used to evaluate the link quality.

3.5 System design and implementation

To achieve the second objective, the proposed method is transformed into a workable prototype using Python. Python is used because it has the required libraries, i.e., those containing built-in modules and the Application Programming Interface (API) that support data processing. There are three steps for evaluating a link quality: link monitoring, link measurements, metric evaluation. Figure 3.2 shows steps for link quality estimation. The prototype evaluates the link quality according to these three steps.

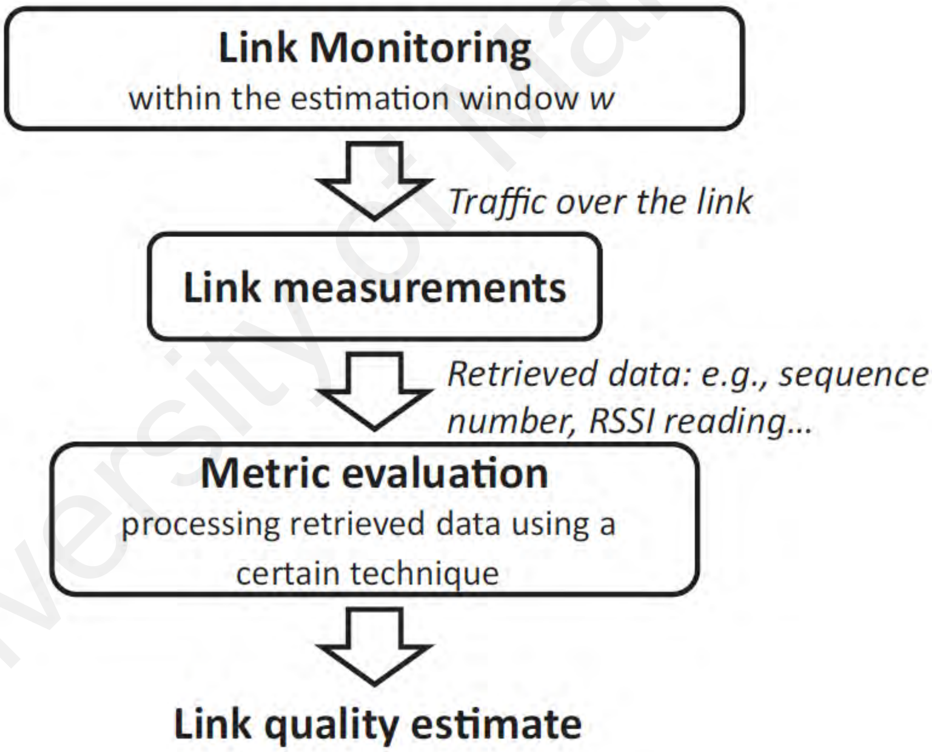


Figure 3.2: Steps for link quality estimation (adapted from Baccour et al., 2012)

3.6 Testing and evaluation

To achieve the last objective, a simulation is used to evaluate the accuracy rate of the proposed method in comparison to the other related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI methods). To make a fair comparison, a similar simulation setup was adapted from the study of (Boano *et al.*, 2010). This contains a sending node and 80 receiving nodes. The sending node is responsible for broadcasting packets while the receiving nodes are responsible for receiving packets and recording the data of the received packets in the log file. The transmission range of sending nodes is 1.8m. The mechanism of this stimulation is used to extract the related data from the log file for each of the tested methods. These extracted data are used to calculate the accuracy rates of the proposed method and the other related works.

3.7 Documentation

The proposed method, the procedures used to conduct the research, and the data obtained from the simulation are documented in this dissertation.

3.8 Chapter summary

This chapter discussed the research methodology that is used in this study. The proposed methodology framework comprises five stages, namely Information Gathering and Analysis, Proposed Method, System Design and Implementation, Testing and Evaluation, and Documentation. Each stage was discussed in detail. The set objectives and how they could be achieved were presented together.

CHAPTER 4: SYSTEM DESIGN AND IMPLENTATION

4.1 Introduction

This chapter presents the design and implementation of the proposed method, which involves the link quality metrics, the architecture and the details of the modules.

4.2 Link quality metrics

Both hardware-based and software-based metrics are used in this study. They are link quality indicator (LQI), signal to noise ratio (SNR) and packet reception ratio (PRR). These three metrics have different characteristics. LQI can be used to distinguish a link that is bad, medium or good (Polastre, Szewczyk, & Culler, 2005). However, it cannot differentiate between a good link and a very good link. According to (Lin *et al.*, 2006), SNR can be used to distinguish a link that is in either good or very good condition. In contrast with LQI, SNR cannot determine whether a link is in bad, medium or good condition. Therefore, by combining both LQI and SNR metrics, the link quality can be categorised into bad, medium, good or very good categories. However, LQI and SNR are hardware-based metrics, and these metrics do not consider packet lost information. Hence this might cause an overestimation of a link quality. As such, there is a need to use PRR (software-based metric) to overcome the lost packet information problem.

4.3 The architecture of the proposed method

Three types of modules, the Fuzzifier module, the Inference module, and the Defuzzifier module, are used in this study. The architecture of the proposed method is shown in Figure 4.1.

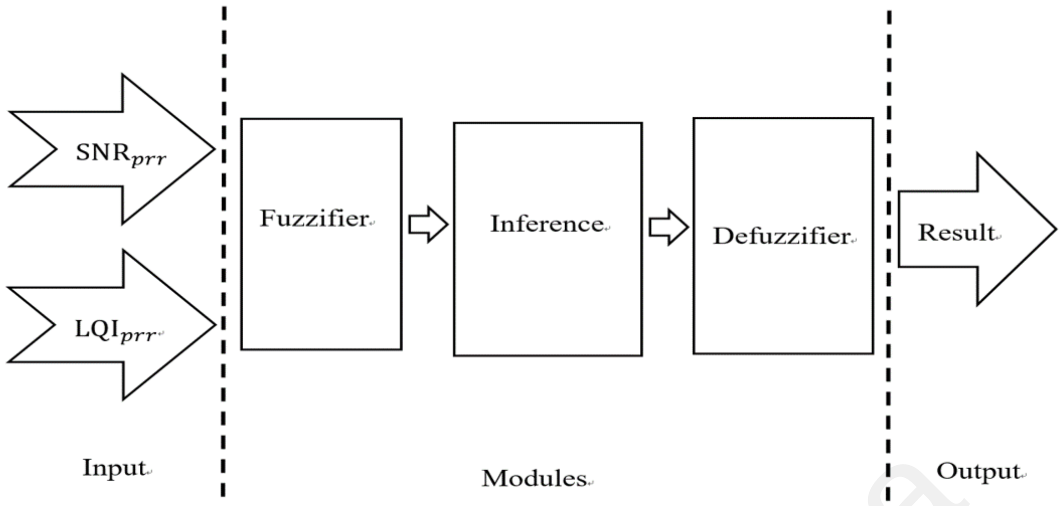


Figure 4.1: The architecture of the proposed method

4.4 The Fuzzifier module

The Fuzzifier module is used to convert the input link quality metrics to their respective fuzzy sets based on several proposed membership functions. There are two inputs in this module, SNR_{prr} and LQI_{prr}. The following equations are used to calculate the two inputs:

$$\text{SNR}_{prr} = \text{SNR}_{mean} * PRR \quad (1)$$

$$\text{LQI}_{prr} = \text{LQI}_{mean} * PRR \quad (2)$$

SNR_{mean} is the average value of SNR and LQI_{mean} is the average value of LQI. To overcome the inherent drawback of hardware-based metrics mentioned earlier, the proposed method uses PRR multiply with the hardware-based metric in the calculation, where the PRR value is calculated based on the division of the number of received packets at the receiver-side with the number of sent packets at the sender-side.

The classic way to evaluate a link quality is by using bad, medium, and good categories. However, recently, this classification was extended to bad, medium, good, and very good categories by (Boano *et al.*, 2010). According to the authors, good quality links might still encounter packet lost problems. Therefore, the very good quality link was introduced to ensure 100% successful packet transmission. Because this distinction was a significant one and as a result, the proposed method adopted the extended classification in our work.

There are four different quality ranks of fuzzy sets in the Fuzzifier module. These are bad quality, medium quality, good quality and very good quality. Each fuzzy set has a unique membership function to deal with each input metric. A membership function is a mapping method that is derived from a space of points in the interval [0, 1] (Yen & Langari, 1999). In classical logic theory, there are only two options (either 0 or 1), where the input metric either belongs to or does not belong to the set. By using a fuzzy logic approach, the parameter range can be extended. Any value within the range of 0 to 1 can be used as an indicator for the degree to which the input metric belongs to the fuzzy set. In this Fuzzifier module, a fuzzy set A of a universe of discourse $X = \{x\}$ is defined as $A = \{x; \mu A(x) \mid \forall\ x \in X\}$, where X is a space of points and $\mu A(x)$ is a membership function of $x \in X$ being an element of A.

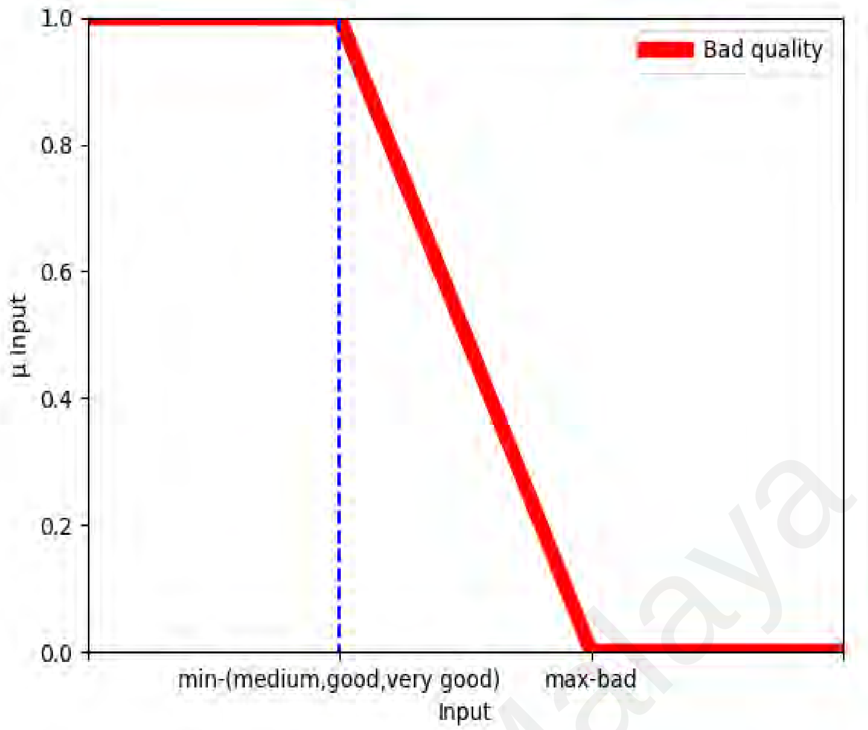


Figure 4.2: The membership function of the bad quality fuzzy set.

The preliminary experiments were conducted to obtain the threshold of the membership functions in the Fuzzifier Module. Figure 4.2 shows the membership function of the bad quality fuzzy set. The membership function of the bad quality fuzzy set is determined by two thresholds – min-(medium, good, very good) and max-bad. The min-(medium, good, very good) is the minimum value of an "Input" in medium quality, good quality, and very good quality. The max-bad is the maximum value of the "Input" in bad quality. "Input" is referred to as either SNR_{prr}or LQI_{prr}. "µ Input" is referred to as the membership function of "Input".

If the values of the "Input" are greater than max-bad, then the link is not bad quality, and the value of the membership function of bad quality fuzzy set is 0. On the other hand, if the values of the "Input" are less than min-(medium, good, very good), the link is confirmed as bad quality, and the value of the membership function of bad quality fuzzy set is 1. When the values of the "Input" are within min-(medium, good, very good) and max-bad, it means that the link partially belongs to the bad quality fuzzy set and the membership function of bad quality fuzzy set is in between 0 to 1.

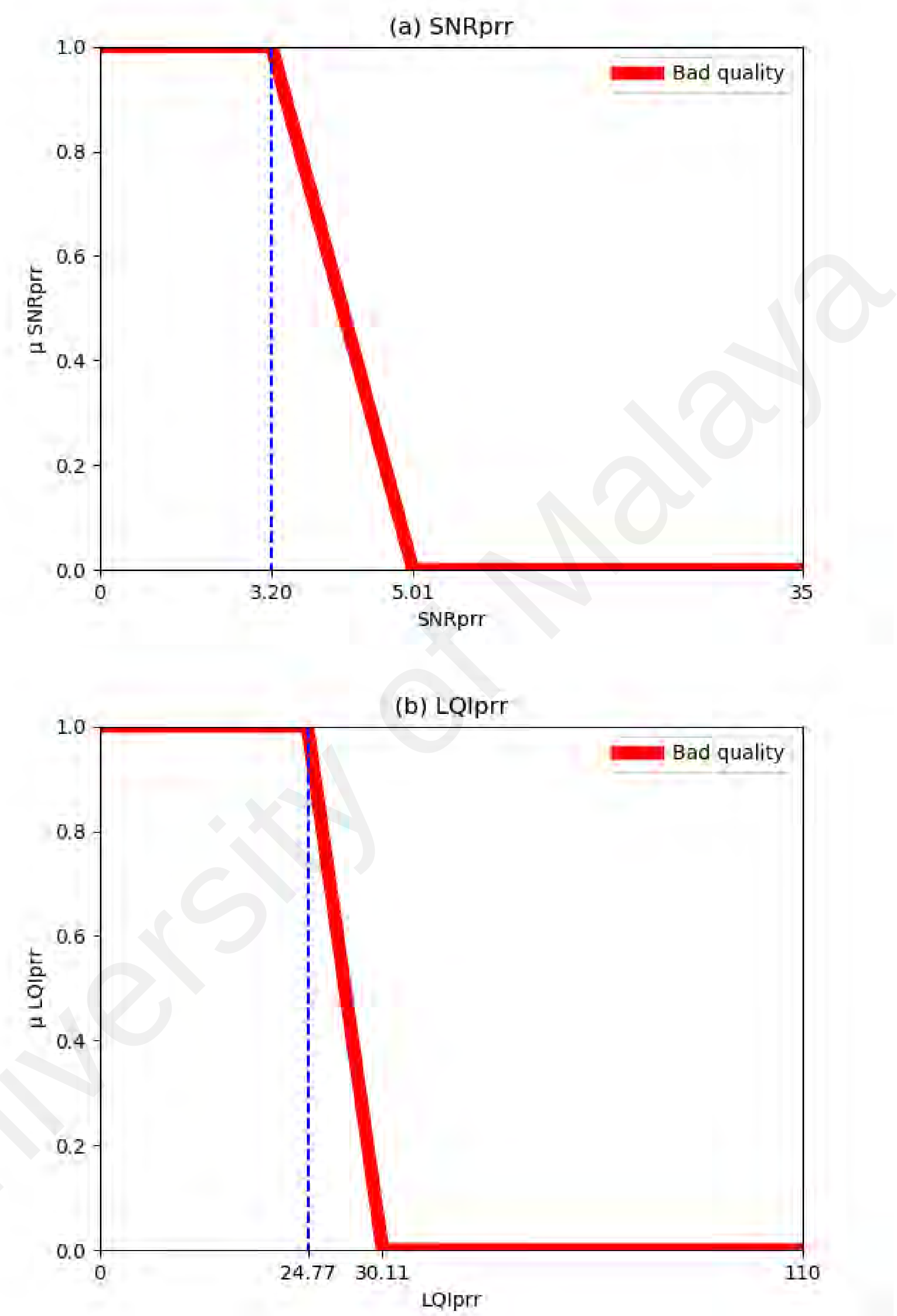


Figure 4.3: The SNR$_{prr}$ and LQI$_{prr}$ membership functions for the bad quality fuzzy set

From the preliminary experiments, the max-bad of SNR$_{prr}$ was found to be 5.01 (see Figure 4.3a). The link is not a bad link if the SNR$_{prr}$ value is greater than or equal to

5.01. The threshold of SNR_{prr} that completely belongs to the bad quality fuzzy set is 3.20. If the SNR_{prr} value is lesser than or equal to 3.20, the link is a bad link. Therefore, a bad link is assigned a membership function of 1 and a membership function of 0 is for those that are not bad links. The membership function is in between 0 to 1 when the SNR_{prr} values are between 3.20 and 5.01.

The max-bad of LQI_{prr} was found to be 30.11 (see Figure 4.3b). The link is not a bad quality link if the LQI_{prr} value of a link is greater than or equal to 30.11. The threshold of LQI_{prr} that completely belongs to the bad quality fuzzy set is 24.77. If the LQI_{prr} value is less than or equal to 24.77, the link is a bad link. Therefore, a bad link is assigned with a membership function of 1 and a membership function of 0 is for those that are not bad links. The membership function is in between 0 to 1 if the LQI_{prr} values are in between 24.77 and 30.

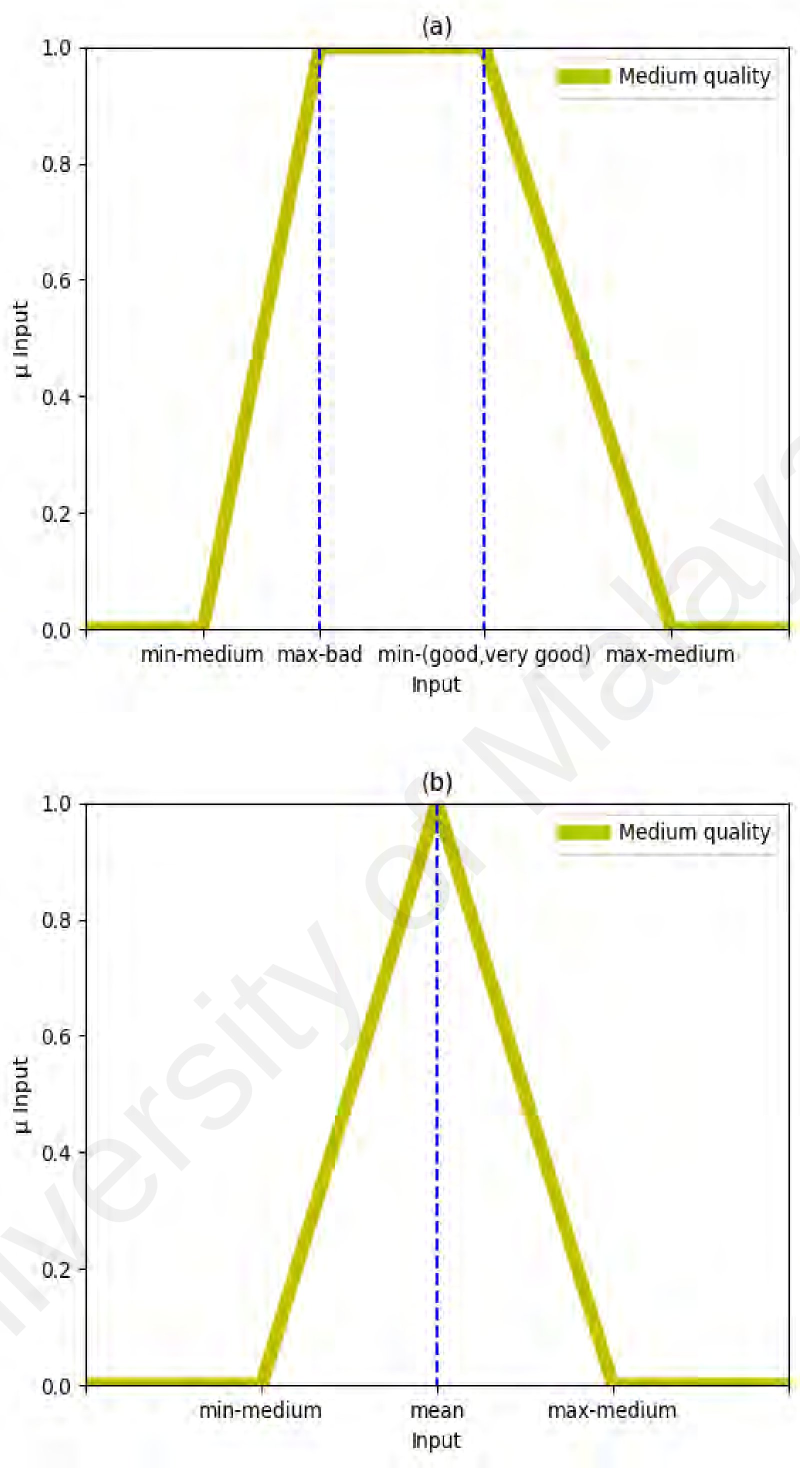


Figure 4.4: The membership function of the medium quality fuzzy set.

Figure 4.4 shows the membership function of the medium quality fuzzy set. The min-medium and max-medium are used to determine the range of an "Input" of the medium quality fuzzy set. The min-medium and max-medium are the minimum and maximum values of an "Input" in medium quality, respectively. If the values of the "Input" are less than the min-medium or greater than the max-medium, the link is not medium quality, and the value of the membership function of medium quality fuzzy set is 0.

There are two cases that are used to determine whether the values of the "Input" falls within the min-medium and the max-medium.

Case 1: max-bad is less than min-(good, very good)

If the values of the "Input" falls between max-bad and min-(good, very good), the link is confirmed as medium quality, and the value of the membership function of medium quality fuzzy set is 1. On the other hand, if the values of the "Input" falls between min-medium and max-bad or min-(good, very good) and max-medium, it means that the link does not completely belong to the medium quality fuzzy set, and the membership function of medium quality fuzzy set is in between 0 to 1 (see Figure 4.4a).

Case 2: max-bad is greater than min-(good, very good)

In this case, the average values of the "Input" (i.e., mean "Input") are computed as being in between the min-medium and the max-medium of the membership function (see Figure 4.4b). If the values of the "Input" are mean, then the value of the membership function of medium quality fuzzy set is 1. On the other hand, if the values of the "Input" falls between min-medium to mean or mean and max-medium, the membership function of medium quality fuzzy set is in between 0 to 1.

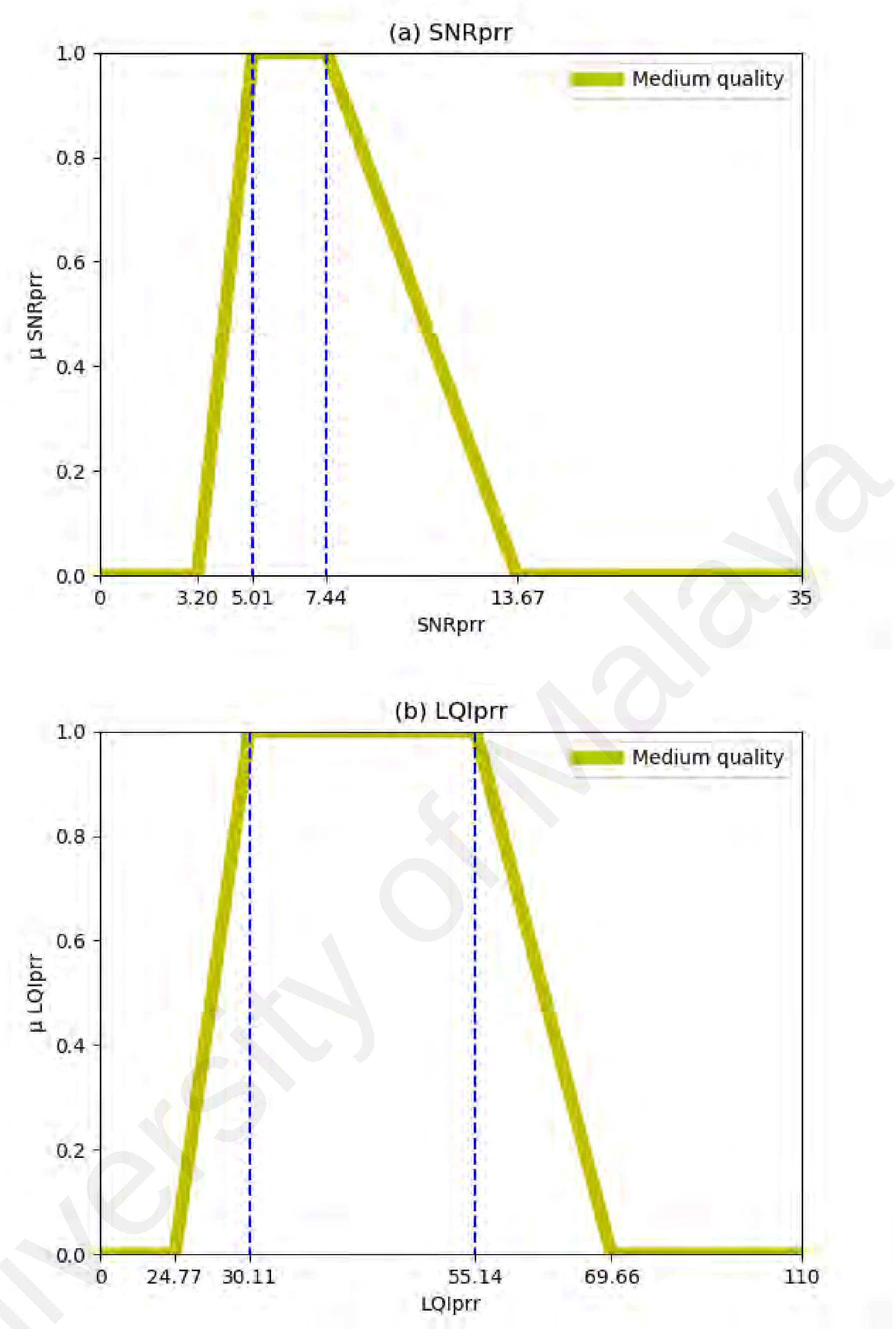


Figure 4.5: The SNR_{prr} and LQI_{prr} membership functions for the medium quality fuzzy set.

From the preliminary experiments, the min-medium and the max-medium of SNR_{prr} were found to be 3.20, and 13.67, respectively (see Figure 4.5a). The link is not a medium link if the SNR_{prr} value of a link is less than or equal to 3.20, or greater than or equal to 13.67. Thus, the membership function of SNR_{prr} is 0 when the link is not a medium link. The thresholds of SNR_{prr} that completely belongs to the medium quality fuzzy set are 5.01 and 7.44. If the SNR_{prr} value of a link is in the range from 5.01 to 7.44, the link is a medium link. Herein, a medium link is assigned a membership function of 1 when the link is a medium link. The membership function in between 0 to 1 is for those SNR_{prr} values that are within the range of 3.20 to 5.01 or 7.44 to 13.67.

The min-medium and the max-medium of LQI_{prr} were 24.77, and 69.66, respectively (see Figure 4.5b). The link is not a medium link if the LQI_{prr} value of a link is less than or equal to 24.77, or greater than or equal to 69.66. The membership function of LQI_{prr} is 0 when the link is not a medium link. The thresholds of LQI_{prr} that completely belong to the medium quality fuzzy set are 30.11 and 55.14. If the LQI_{prr} value of a link is within the range of 30.11 to 55.14, the link is a medium link, and it is assigned a membership function of 1. The LQI_{prr} values that are within the range of 24.77 to 30.11 or 55.14 to 69.66 are assigned the membership function in between 0 to 1.

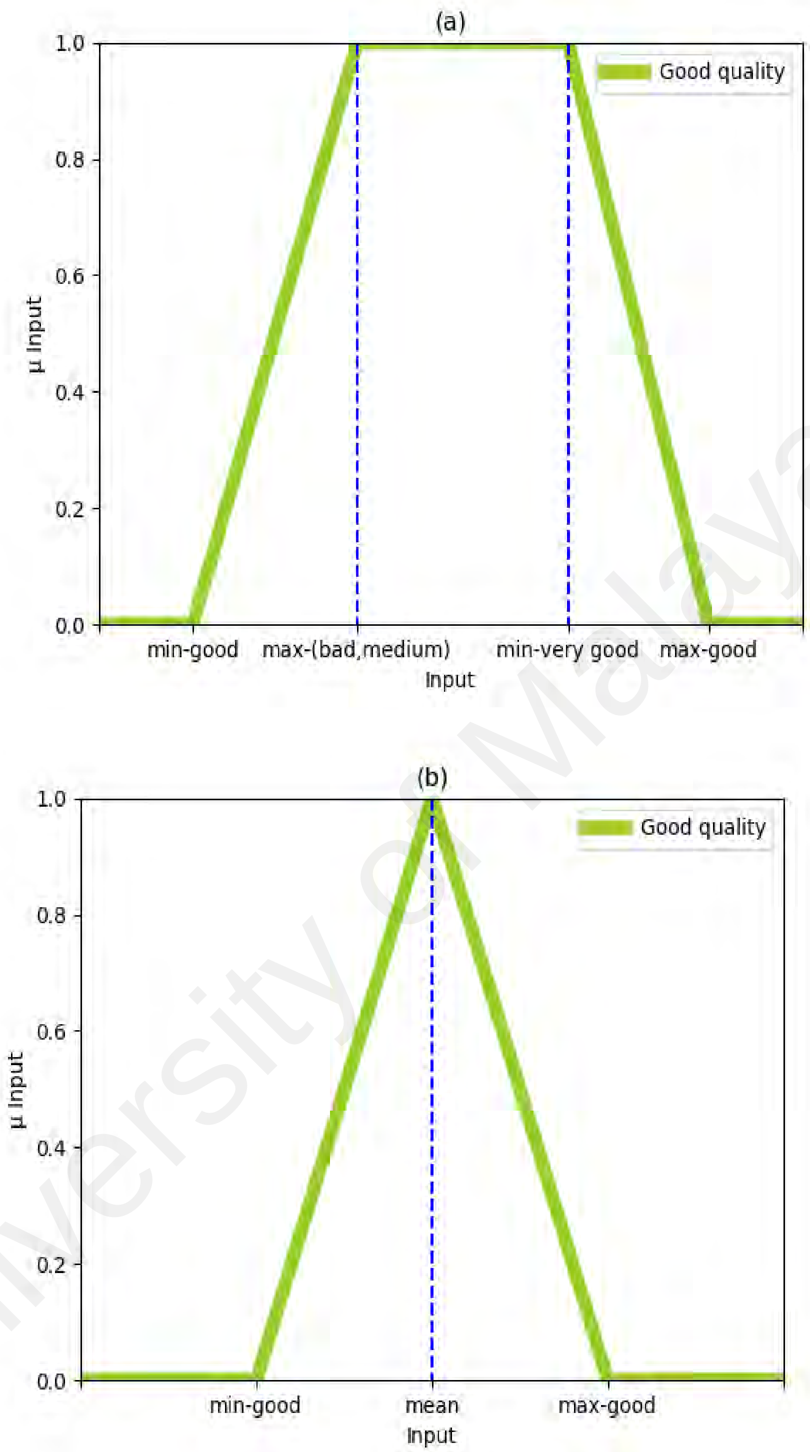


Figure 4.6: The membership function of the good quality fuzzy set.

Figure 4.6 shows the membership function of the good quality fuzzy set. The min-good and max-good are used to determine the range of an "Input" of the good quality fuzzy set. The min-good and max-good are the minimum and maximum values of an

“Input” in good quality, respectively. If the values of the “Input” are less than the min-good or greater than the max-good, the link is not good quality, and the value of the membership function of good quality fuzzy set is 0.

There are two cases that are used to determine whether the values of the “Input” fall within min-good and max-good.

Case 1: max-(bad, medium) is less than min-very good

If the values of the “Input” fall between max-(bad, medium) and min-very good, then the link is confirmed as good quality and the value of the membership function of good quality fuzzy set is 1. On the other hand, if the values of the “Input” fall between min-good and max-(bad, medium) or min-very good and max-good, it means that the link does not completely belong to the good quality fuzzy set and the membership function of good quality fuzzy set is in between 0 to 1 (see Figure 4.6a).

Case 2: max-(bad, medium) is greater than min-very good

In this case, the average values of the “Input” (i.e., mean “Input”) are computed to be between the min-good and the max-good of the membership function (see Figure 4.6b). If the values of the “Input” are mean, the value of the membership function of good quality fuzzy set is 1. On the other hand, if the values of the “Input” fall between min-good to mean or mean to max-good, the membership function of good quality fuzzy set is in between 0 to 1.

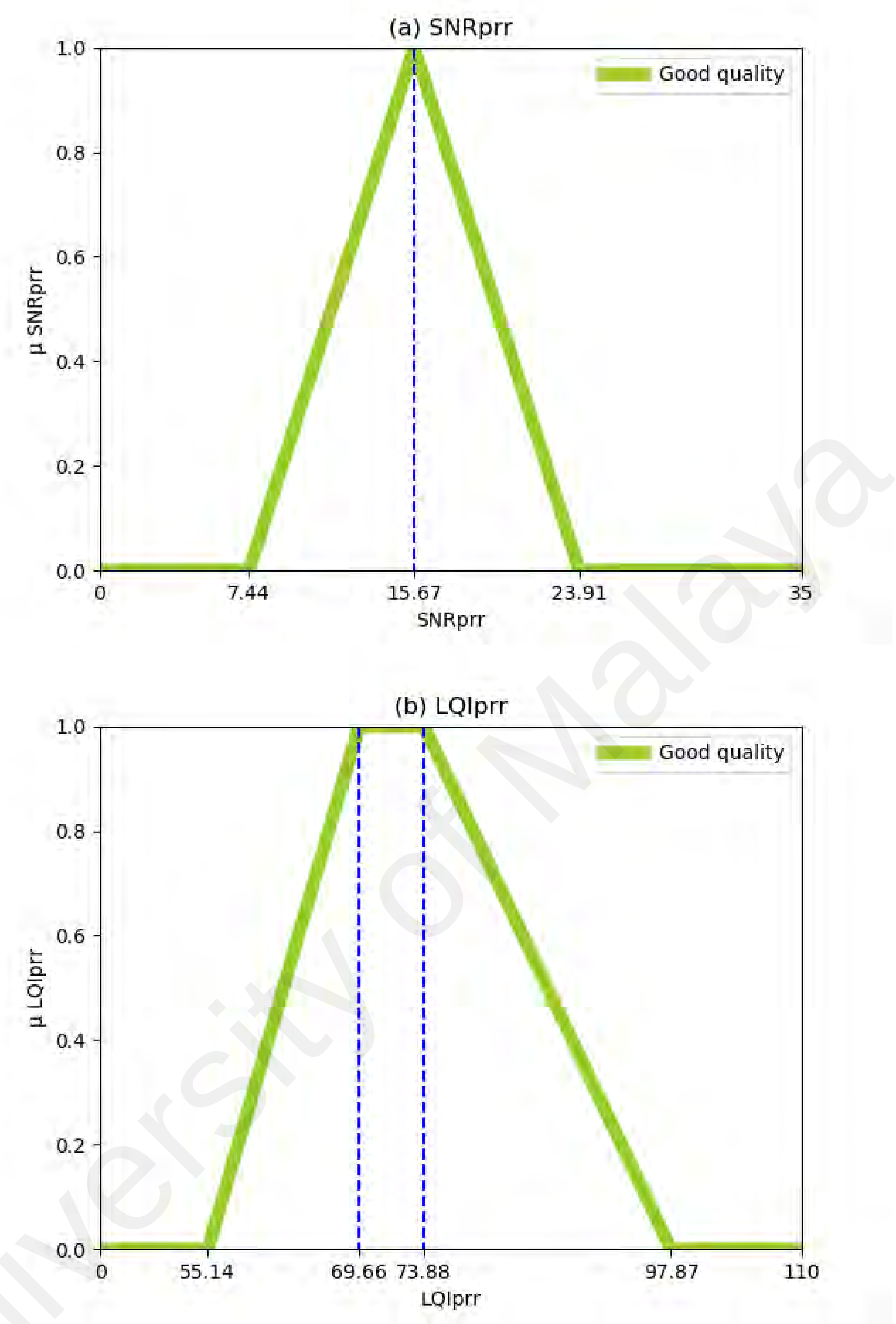


Figure 4.7: The SNR_{prr} and LQI_{prr} membership functions for the good quality fuzzy set

From the preliminary experiments, the min-good and the max-good of SNR_{prr} were found to be 7.44, and 23.91, respectively (see Figure 4.7a). If the SNR_{prr} value of a link is less than or equal to 7.44, or greater than or equal to 23.91, the link is not a good link. The membership function of SNR_{prr} is 0 when the link is not a good link. The SNR_{prr}

values that are in between 7.44 and 23.91 are assigned the membership function in between 0 to 1.

The min-good and the max-good of LQI_{prr} were 55.14, and 97.87, respectively (see Figure 4.7b). If the LQI_{prr} value of a link is less than or equal to 55.14, or greater than or equal to 97.87, the link is not a good link. The membership function of LQI_{prr} is 0 when the link is not a good link. The thresholds of LQI_{prr} that completely belong to the good quality fuzzy set are 69.66 and 73.88. If the LQI_{prr} value of a link is within the range of 69.66 and 73.88, the link is a good link, and it is assigned a membership function of 1. The LQI_{prr} values that are within the range of 55.14 to 69.66 and 73.88 to 97.87 are assigned the membership function in between 0 to 1.

Figure 4.8: The membership function of the very good quality fuzzy set.

Figure 4.8 shows the membership function of the very good quality fuzzy set. The membership function of the very good quality fuzzy set is determined by two thresholds

– min-very good and max-(bad, medium, good). The min-very good is the minimum value of an “Input” in very good quality. The max-(bad, medium, good) is the maximum value of the “Input” in bad quality, medium quality, and good quality. If the values of the “Input” are greater than max-(bad, medium, good), the link is confirmed as very good quality, and the value of the membership function of very good quality fuzzy set is 1. On the other hand, if the values of the “Input” are less than min-very good, the link is not very good quality, and the value of the membership function of very good quality fuzzy set is 0. When the values of the “Input” are within min-very good and max-(bad, medium, good), the link partially belongs to the very good quality fuzzy set and the membership function of very good quality fuzzy set is in between 0 to 1.

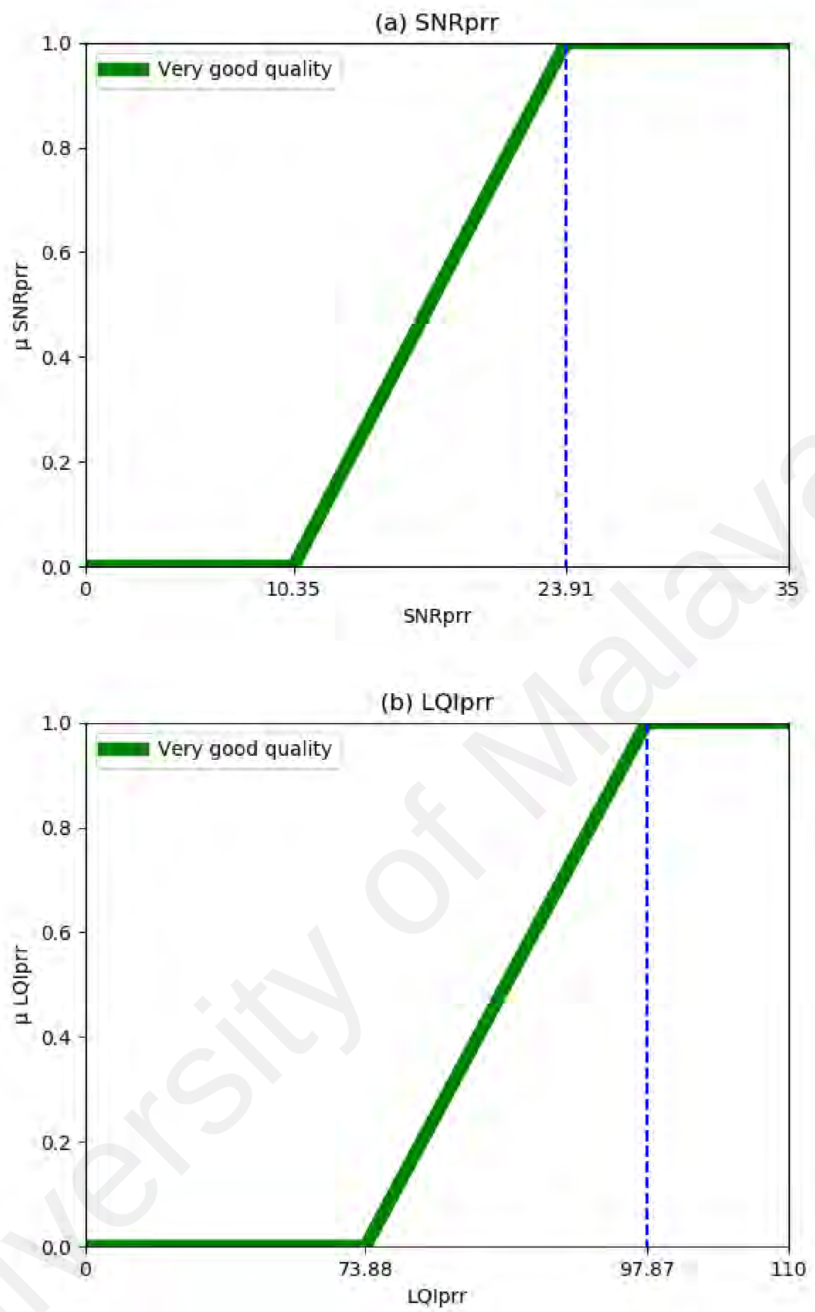


Figure 4.9: The SNR_{prr} and LQI_{prr} membership functions for the very good quality fuzzy set

From the preliminary experiments, the min-very good of SNR_{prr} was found to be 10.35 (see Figure 4.9a). If the SNR_{prr} value of a link is less than or equal to 10.35, the link is not a very good link. The threshold of SNR_{prr} that completely belongs to the very good quality fuzzy set is 23.91. Herein, the link is a very good link if the SNR_{prr}

value is greater than or equal to 23.91. Such a very good link is then assigned a membership function of 1. A link that is not a very good link is assigned a membership function of 0. SNR_{prr} values that are within the range of 10.35 to 23.91 are assigned the membership function in between 0 to 1.

The min-very good of LQI_{prr} was found to be 73.88 (see Figure 4.9b). A link is not a very good link if the LQI_{prr} value of a link is less than or equal to 73.88. The threshold of LQI_{prr} that completely belongs to the very good quality fuzzy set is 97.87. If the LQI_{prr} value is greater than or equal to 97.87, the link is a very good link. This link is then assigned a membership function of 1, while not very good links are assigned a membership function of 0. The LQI_{prr} values between 73.88 and 97.87 are assigned the membership function in between 0 to 1.

4.5 The Inference module

The Inference module is used to simulate the process of human reasoning. This module derives the rule outputs based on the proposed fuzzy rules and the given inputs obtained from the Fuzzifier module. The proposed fuzzy rules are the rules based on fuzzy sets, and they can assist the Inference module to complete reasoning.

There are two "Inputs" used ($\mathrm{SNR}_{prr}$and LQI_{prr}), but the final result of the link quality produced by both "Inputs" can only belong to one of the four qualities (very good, good, medium or bad quality). As a result, the proposed method only need four fuzzy rules to cater for all possible combinations. The four proposed fuzzy rules are as follows:

Rule: 1

IF the final result of both SNR_{prr} **AND** LQI_{prr} is fallen within the threshold of the very good quality fuzzy set, **THEN** the link quality is very good.

Rule: 2

IF the final result of both SNR_{prr} **AND** LQI_{prr} is fallen within the threshold of the good quality fuzzy set, **THEN** the link quality is good.

Rule: 3

IF the final result of both SNR_{prr} **AND** LQI_{prr} is fallen within the threshold of the medium quality fuzzy set, **THEN** the link quality is medium.

Rule: 4

IF final result of both SNR_{prr} **AND** LQI_{prr} is fallen within the threshold of the bad quality fuzzy set, **THEN** the link quality is bad.

This proposed method is based on Yager's study, which used “and-like” and “or-like” operators instead of using the min-max logic proposed by (Zadeh, 1975) to translate fuzzy rules into mathematical expressions (Yager, 1988). The min-max logic translated AND (OR) to min (max) operator, and the result of the expression is determined using only a single value. For example, AND can only take the smallest fuzzy set value, and OR takes the largest fuzzy set value. Therefore, “and-like” and “or-like” operators can consider all values in each fuzzy set based on a weight factor β.

Equation (3), equation (4), equation (5) and equation (6) are the mathematical expressions for Rule 1, Rule 2, Rule 3 and Rule 4, respectively.

$$\mu_{\mathrm{verygood}}(\mathrm{i}) = \beta \cdot \min\left(\mu_{\mathrm{lqi-verygood}}(\mathrm{i}), \mu_{\mathrm{snr-verygood}}(\mathrm{i})\right) + (1-\beta) \cdot \mathrm{mean}\left(\mu_{\mathrm{lqi-verygood}}(\mathrm{i}), \mu_{\mathrm{snr-verygood}}(\mathrm{i})\right) \quad (3)$$

$$\mu_{\mathrm{good}}(\mathrm{i}) = \beta \cdot \min\left(\mu_{\mathrm{lqi-good}}(\mathrm{i}), \mu_{\mathrm{snr-good}}(\mathrm{i})\right) + (1-\beta) \cdot \mathrm{mean}\left(\mu_{\mathrm{lqi-good}}(\mathrm{i}), \mu_{\mathrm{snr-good}}(\mathrm{i})\right) \quad (4)$$

$$\mu_{\mathrm{medium}}(\mathrm{i}) = \beta \cdot \min\left(\mu_{\mathrm{lqi-medium}}(\mathrm{i}), \mu_{\mathrm{snr-medium}}(\mathrm{i})\right) + (1-\beta) \cdot \mathrm{mean}(\mu_{\mathrm{lqi-medium}}(\mathrm{i}), \mu_{\mathrm{snr-medium}}(\mathrm{i})) \quad (5)$$

$$\mu_{\mathrm{bad}}(\mathrm{i}) = \beta \cdot \min\left(\mu_{\mathrm{lqi-bad}}(\mathrm{i}), \mu_{\mathrm{snr-bad}}(\mathrm{i})\right) + (1-\beta) \cdot \mathrm{mean}(\mu_{\mathrm{lqi-bad}}(\mathrm{i}), \mu_{\mathrm{snr-bad}}(\mathrm{i})) \quad (6)$$

$\mu_{\mathrm{verygood}}(\mathrm{i})$, $\mu_{\mathrm{good}}(\mathrm{i})$, $\mu_{\mathrm{medium}}(\mathrm{i})$, and $\mu_{\mathrm{bad}}(\mathrm{i})$ are the membership functions of link i for very good quality, good quality, medium quality, and bad quality fuzzy sets, respectively. $\mu_{\mathrm{lqi-verygood}}(\mathrm{i})$, $\mu_{\mathrm{lqi-good}}(\mathrm{i})$, $\mu_{\mathrm{lqi-medium}}(\mathrm{i})$, and $\mu_{\mathrm{lqi-bad}}(\mathrm{i})$ are the membership functions of LQI_{prr} for the different quality fuzzy sets. $\mu_{\mathrm{snr-verygood}}(\mathrm{i})$, $\mu_{\mathrm{snr-good}}(\mathrm{i})$, $\mu_{\mathrm{snr-medium}}(\mathrm{i})$, and $\mu_{\mathrm{snr-bad}}(\mathrm{i})$ are the membership functions of SNR_{prr} for different quality fuzzy sets. Weight factor β is a constant value in between 0 to 1. The recommended values for β are in the range of [0.5 ... 0.8] where 0.6 usually gives the best result (Youssef, Sait, & Khan, 2001). Therefore, the β value implemented in this study is 0.6.

4.6 The Defuzzifier module

The Defuzzifier module is designed to aggregate the rule outputs that are inferred from the Inference module. The centre of gravity (COG) is used to aggregate the membership function of different fuzzy sets (Cox, Taber, & O'Hagen, 1998). COG is one of the most commonly found methods used by many fuzzy logic systems in previous studies (Collan, Fedrizzi, & Luukka, 2015; Di Martino & Sessa, 2018; Hossain *et al.*, 2016; Rustamov, 2018; Yasuda, 2011). The calculation of COG used in the Defuzzier module is stated in the equation below.

$$\text{Result} = \frac{\mu_{bad}(i)*17.5\%+\mu_{medium}(i)*40\%+\mu_{good}(i)*87.5\%+\mu_{verygood}(i)*100\%}{\mu_{bad}(i)+\mu_{medium}(i)+\mu_{good}(i)+\mu_{verygood}(i)} \qquad (7)$$

$\mu_{\text{bad}}(\text{i})$, $\mu_{\text{medium}}(\text{i})$, $\mu_{\text{good}}(\text{i})$, and $\mu_{\text{verygood}}(\text{i})$ are the membership functions of link i for the bad quality, medium quality, good quality, and very good quality fuzzy set, respectively. The sample points of the bad quality, medium quality, good quality, and very good quality fuzzy sets are 17.5%, 40%, 87.5%, and 100%, respectively. These sample points are calculated according to the average threshold of the different link qualities. Table 4.1 shows the results of the membership function values of both $\text{SNR}_{prr}$and LQI_{prr}.

Table 4.1: Results of the membership function values of both SNR_{prr}AND LQI_{prr}

SNR_{prr} / LQI_{prr}	Very good	Good	Medium	Bad
Very good	100%	93.73%	70%	58.75%
Good	93.73%	87.5%	63.75%	52.5%
Medium	70%	63.75%	40%	28.75%
Bad	58.75%	52.5%	28.75%	17.5%

After calculating the membership function values of both SNR_{prr} AND LQI_{prr}, each link quality is then classified based on the rules adopted from the study of (Boano *et al.* 2010). The following are the classification rules and the results of the classification can be viewed in Table 4.2.

(i) A link is classified as a bad quality link if 0% ≤ Result < 35%

(ii) A link is classified as a medium quality link if 35% ≤ Result < 75%

(iii) A link is classified as a good quality link if 75% ≤ Result < 100%

(iv) A link is classified as a very good quality link if Result = 100%.

Table 4.2: The classification results

SNR_{prr} \ LQI_{prr}	Very good	Good	Medium	Bad
Very good	Very good	Good	Medium	Medium
Good	Good	Good	Medium	Medium
Medium	Medium	Medium	Medium	Bad
Bad	Medium	Medium	Bad	Bad

4.7 Chapter summary

In this Chapter, the design and implementation of the proposed method were presented. The proposed method consists of the following modules: the Fuzzifier module, the Inference module, and the Defuzzifier module. The Fuzzifier module was used to convert the input link quality metrics to their respective fuzzy sets based on several proposed membership functions. The membership functions of each metric were determined by performing preliminary experiments. The Inference module was used to imitate the inference process of a human. The rule output was obtained in accordance with the proposed fuzzy rules and the given input acquired from the Fuzzifier module. These fuzzy rules were translated to equations using “and-like” and “or-like” operators to calculate the rule output. The Defuzzifier module was used to aggregate the rule outputs inferred from the Inference module. The result from the Defuzzifier module was used to evaluate the link quality.

CHAPTER 5: TESTING AND ANALYSIS

5.1 Introduction

This chapter discusses the testing and analysis stages of this study, including the simulation setup and the evaluation of the proposed method.

5.2 Simulation setup

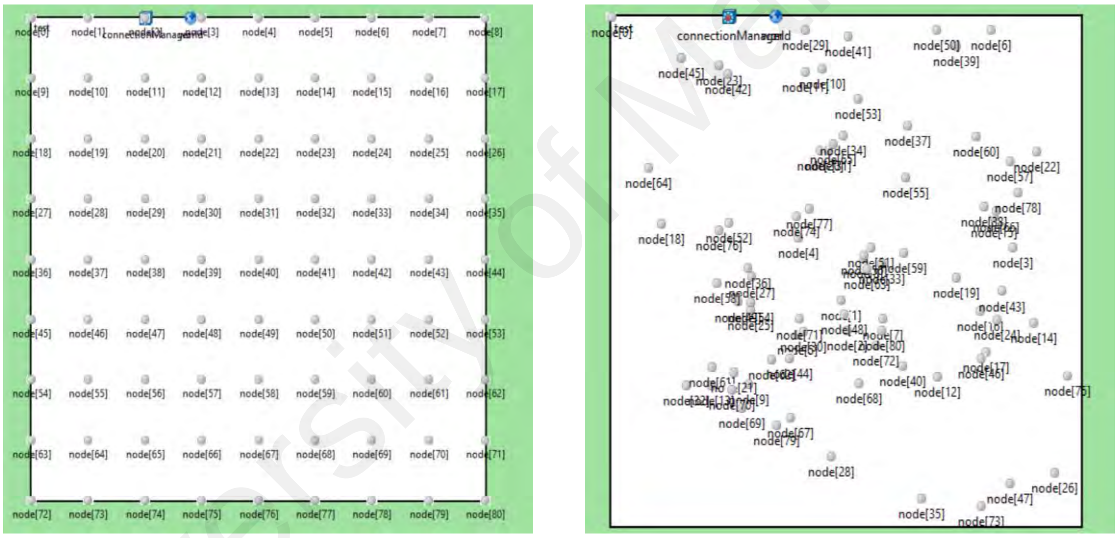
The simulation setup and initial deployment for evaluating the proposed method are shown in Table 5.1. The simulation used OMNeT++ and MiXiM to simulate the packets transmission. OMNeT++ is a modular and open network simulator platform based on components. MiXiM is an extended simulator in OMNeT++. The simulation used BaseNetwork as the environment module and Host802154_2400MHz as the node module. Host802154_2400MHz uses a transceiver based on IEEE802.15.4 standard at 2.4 GHz for wireless transmission. This setup of the experiment and its initial deployment were adapted from the study of (Boano *et al.*, 2010) for determining better link quality criteria.

Table 5.1: The simulation setup and initial deployment (adapted from Boano *et al.*, 2010)

Deployment area:	240m x 240m
Distance between each node:	30m
Number of nodes:	81
Broadcast node:	node[0]
Transmission Power:	1mW
Radio transceiver:	2.4 GHz Chipcon CC2420
Mobility model:	Random Waypoint
Mobility speed:	1 m/s (the receiving node) 0 m/s (the sending node)
Number of packets	100 000
Frequency of broadcast packets	1 packet/s

The area of deployment is 240 m x 240 m. The distance between each node is 30 m. There are two types of nodes used in the simulation, the sending node and the receiving node. The sending node is responsible for broadcasting packets. The receiving node is responsible for receiving the packet and recording the data in the log file. The number of nodes used in the simulation is 81. The broadcast node or sending node is set as node[0]. Other nodes are set as the receiving nodes. The transmission power of the sending node is 1 mW. The radio transceiver of nodes is 2.4 GHz Chipcon CC2420. The mobility model is Random Waypoint. The speed of the receiving nodes is 1 m/s. The speed of the sending node is 0 m/s. The number of packets is 100,000, and the frequency of broadcast packets is one packet per second. After deployment, the receiving nodes are constantly moving randomly (see Figure 5.1).

According to (Boano *et al.* 2010), the purpose of having only one broadcast node and a sending node that does not move is to simplify the process of obtaining the required data. Although the sending node does not move, the distance between the sending node and the receiving node is changing dynamically after the initial deployment. The simulation setting and deployment are different from the real packet transmission process, but the proposed method can be used to evaluate link quality in real networks. This is because the link quality is evaluated based on the data of the received packets. Many of the benchmark methods adopt this simulation setting and deployment to evaluate a link quality.



(a) Initial deployment (b) Random positions after deployment

Figure 5.1: The position of nodes before and after deployment (adapted from Boano *et al.*, 2010)

5.3 Evaluation method

The data extraction mechanism used in this study is shown in Figure 5.2. The related data is extracted from the log file for each of the tested methods to calculate the accuracy rate of the tested method.

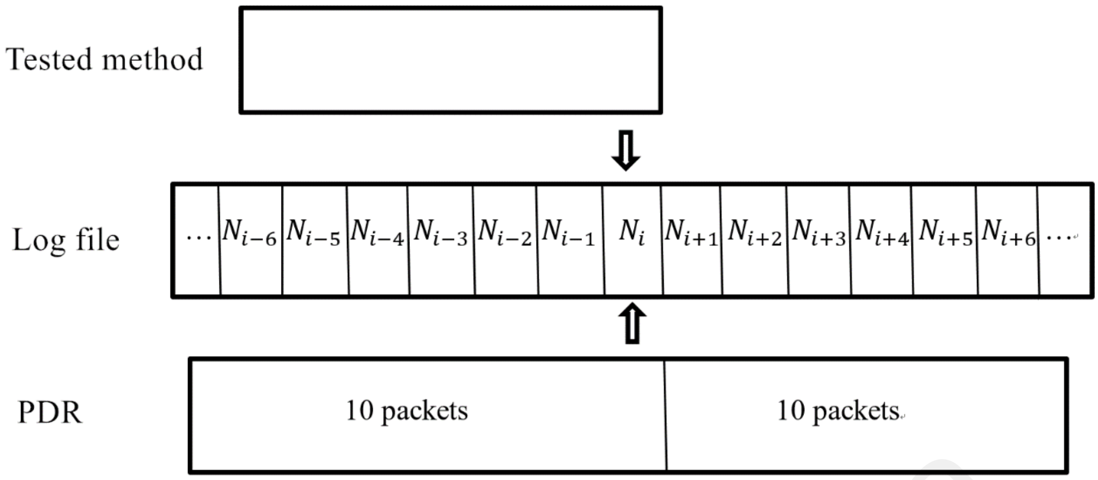


Figure 5.2: Data extraction mechanism (adapted from Boano *et al.*, 2010)

The data extraction mechanism is divided into three parts, namely the tested method, log file, and packet delivery ratio (PDR). For each of the tested method, the data in the log file are collected from N_i and before N_i (historical data) to evaluate the link quality at N_i. Each block (such as N_i) in the log file represents the data of a successfully received packet. The data that consist of software-based metrics (PRR), hardware-based metrics (SNR/LQI), or both software-based and hardware-based metrics, are extracted from the log file to be further analysed by the related methods.

The packet delivery ratio (PDR) is calculated using both historical and future data. Historical data are the data collected from N_i and before N_i , and future data are the data collected after N_i where i is a positive integer. The size of each of the historical data and future data is 10 packets. The link quality is stable only for a short period of time (Srinivasan *et al.*, 2010). Therefore, the packet size of PDR must not be too large. Based on the heuristic approach, the size of the PDR was determined as 20 packets, and the precision of PDR can reach up to 5%. This precision level is adequate for evaluating the link quality.

The link quality at N_i is evaluated based on the scales adapted from previous studies (Boano *et al.*, 2010; Liu *et al.*, 2014; Aswale *et al.*, 2017) where:

(i) A link is classified as a bad quality link if 0% ≤ PDR < 35%

(ii) A link is classified as a medium quality link if 35% ≤ PDR < 75%

(iii) A link is classified as a good quality link if 75% ≤ PDR < 100%

(iv) A link is classified as a very good quality link if PDR = 100%

The accuracy rate of the tested method is calculated using the following equation where $N_{successful}$ is the number of link qualities that are successfully evaluated, and N_{total} is the total number of link qualities.

$$\text{The accuracy rate} = \frac{N_{successful}}{N_{total}} \quad (8)$$

5.4 Results analysis

Two evaluations are conducted in this study. These are i) comparison of the proposed method, PRR, SNR and LQI, and ii) comparison of the proposed method with other related works.

5.4.1 Comparison of the proposed method, PRR, SNR and LQI

The accuracy rates of the proposed method, hardware-based metrics and software-based metrics are shown in Figure 5.3. The number of packets shown at x-axis in the figure refers to the number of packets used to evaluate a link quality. It is different from the number of packets in Table 5.1, which refers to the total number of packets sent in the experiment. The proposed method has the highest accuracy rate when compared to each individual hardware-based and software-based metrics. Specifically, the accuracy rates of the proposed method are approximately 18.37%, 26.94%, 44.45% higher than PRR, SNR, and LQI, respectively. PRR (software-based metric) has the second highest accuracy rate when compared to LQI and SNR (hardware-based metrics) except for packet size 1 and 2. The accuracy rate of SNR is higher than PRR when the packet size is 1 and 2. This means that PRR is not suitable for use in evaluating the link quality if the packet size is too small. However, it can evaluate the link quality better than hardware-based metrics if the number of packages is large enough. LQI has the lowest accuracy rate in comparison to the proposed method, PRR, and SNR. To conclude, the proposed method, by combining the hardware-based and software-based metrics together, can evaluate the link quality better than each individual hardware-based and software-based metrics. The proposed method has a higher accuracy rate because it uses both hardware-based and software-based metrics. To combine hardware-based and software-based metrics could overcome some drawbacks of individual hardware-based and software-based metrics.

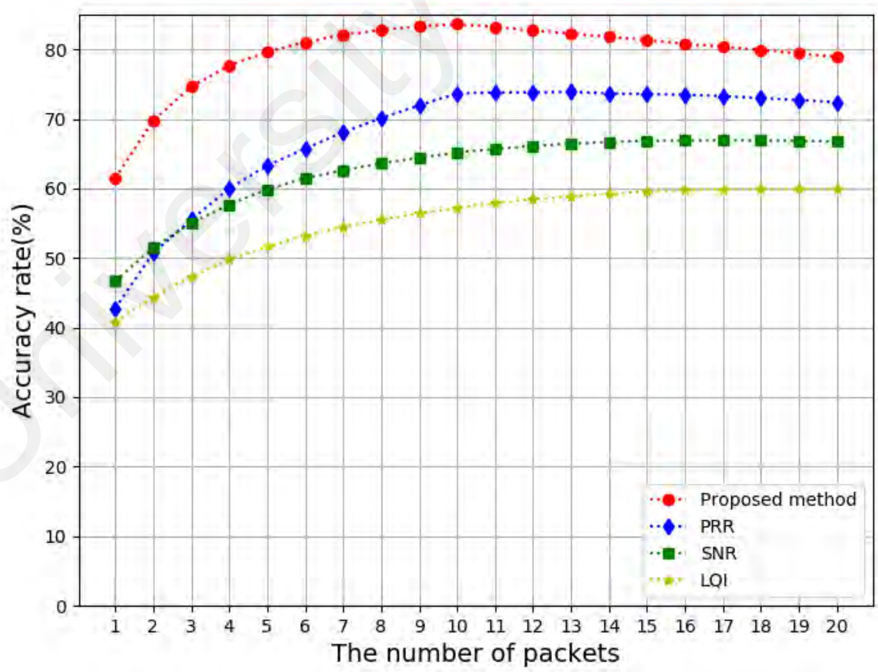


Figure 5.3: The accuracy rates of the proposed method, hardware-based metrics and software-based metrics

The T test was used to evaluate whether the accuracy rate of the proposed method and individual input metrics are correlated. Since there are three input metrics, there are three groups of hypothesis formulated as following:

PRR:

H_0: There is no statistically significant difference between the proposed method and PRR with respect to the accuracy rate.

H_1: There is a statistically significant difference between the proposed method and PRR with respect to the accuracy rate.

SNR:

H_0: There is no statistically significant difference between the proposed method and SNR with respect to the accuracy rate.

H_1: There is a statistically significant difference between the proposed method and SNR with respect to the accuracy rate.

LQI:

H_0: There is no statistically significant difference between the proposed method and LQI with respect to the accuracy rate.

H_1: There is a statistically significant difference between the proposed method and LQI with respect to the accuracy rate.

Table 5.2: The T test result of hardware-based metrics and software-based metrics compared with the proposed method

Metrics	PRR	SNR	LQI
p-value	3.00×10^{-5}	3.45×10^{-11}	4.1×10^{-16}

Table 5.2 shows the p-value of T test of each individual hardware-based metrics and software-based metrics compare with the proposed method. The p-value of PRR, SNR, and LQI are 3.00×10^{-5}, 3.45×10^{-11} , and 4.1×10^{-16}, respectively. Since all the p-values are lesser than 0.05, all three null hypotheses (H_0) were rejected (Schumacker & Tomek 2013). In other words, there are statistically significant differences between the proposed method and the individual input metrics with respect to the accuracy rate.

5.4.2 Comparison of the proposed method and other related works

The accuracy rates of the proposed method and other related works - Triangle Metric, Window Mean with Exponentially Weighted Moving Average (WMEWMA), improved-LQI, effective-SNR, Link Quality Estimation node (LQE-node) and Channel State Information (CSI), are shown in Figure 5.4. The proposed method had the highest accuracy rate compared to other related works. The accuracy rates of the proposed method were approximately 7.99%, 13.71%, 14.74%, 23.24%, 27.76%, and 39.89% higher than Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI, respectively.

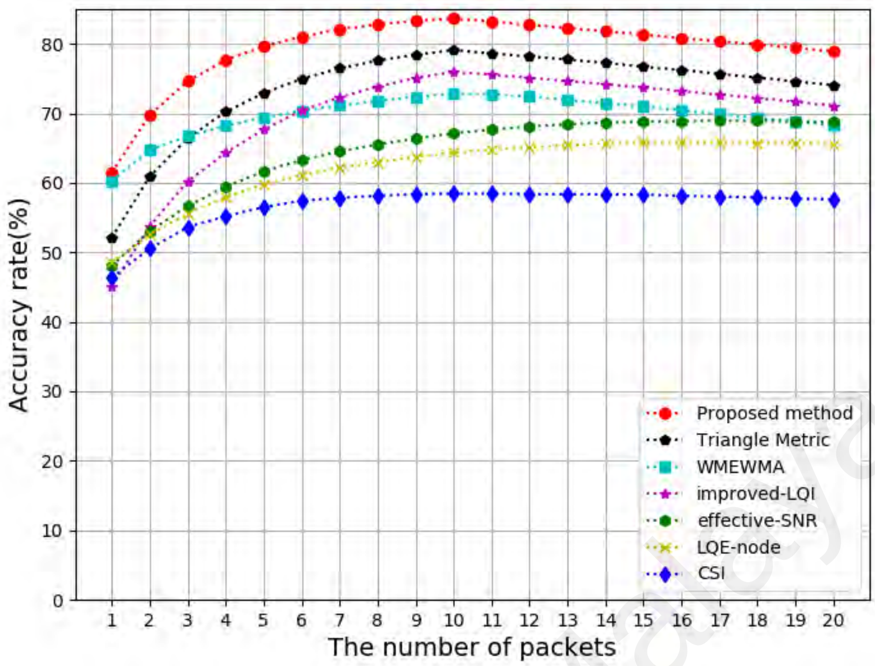


Figure 5.4: The accuracy rates of the proposed method and other related works

The Triangle Metric method had the second highest accuracy rate compared to the other related works except for packet size 1, 2 and 3. This Triangle Metric method uses the Pythagorean theorem to combine hardware-based metrics (SNR and LQI) and software-based metrics (PRR) to evaluate link quality. Nevertheless, the proposed method with its inclusion of fuzzy logic had better outcomes than the related works.

At packet size 1, 2 and 3, WMEWMA had the second highest accuracy rate when compared to the other related works. The ranking of the accuracy rate for WMEWMA dropped from third place (at packet size 4, 5 and 6) to fourth (at packet size 7 until 19) and finally to fifth place at packet size 20. Notably, although WMEWMA used the Exponentially Weighted Moving Average (EWMA) filter to calculate PRR, its accuracy rate was still lower than the methods that contain both hardware-based and software-based metrics.

The accuracy rate for improved-LQI had the lowest accuracy rate when compared with the other related works at packet size 1. However, the accuracy rate for improved-LQI increased from packet size 2 until 6 and become consistent at the ranking of third place from packet size 7 until 20. This improved-LQI method used both successfully and unsuccessfully received packets to calculate the mean value of LQI. It had a higher accuracy rate than other hardware-based metric methods that only considered the LQI value of the successfully received packets.

The CSI method had the lowest accuracy rate when compared with the proposed method and other related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR and LQE-node) except for packet size 1. The LQE-node and the effective-SNR methods also had lower accuracy rates when compared to the proposed method and other related works. The CSI method used normalising RSSI (hardware-based metric) and LQI to evaluate link quality. The LQE-node also used RSSI to evaluate a link quality, in which it considered the influence of the multipath and interference. The effective-SNR method used the Kalman filter to combine SNR and LQI to evaluate link quality. These three methods had lower accuracy rates than the proposed method and other related works as these methods only considered multiple hardware-based metrics to evaluate the link quality.

In conclusion, the proposed method had a higher accuracy rate compared to other related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI method). Although the proposed method and Triangle Metric both use hardware-based and software-based metrics to evaluate link quality, the accuracy rate of the proposed method is higher than the accuracy of Triangle Metric. The difference between them is that the proposed method uses fuzzy logic to combine two types of input metrics and Triangle Metric uses the Pythagorean theorem to combine input metrics. Therefore, the result justified that the fuzzy logic is better than the Pythagorean theorem to combine input metrics. Other methods had lower accurate than the proposed method. The reason is that they only consider the same type of metrics (hardware-based or software-based metrics) to evaluate link quality.

5.5 Chapter summary

The simulation setup and the evaluation method used were presented. The simulation results showed that the proposed method evaluated the link quality better than any individual hardware-based and software-based metrics. Moreover, the proposed method also had a higher accuracy rate compared to other related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI method). The evaluation results have shown that the proposed method, which uses fuzzy logic to evaluate the hardware-based and software-based metrics, can yield a better accuracy rate in evaluating the link quality.

CHAPTER 6: CONCLUSION

6.1 Introduction

This chapter presents the conclusion of this study, elaborating on the achievement of its stated objectives, its contributions to the field, and directions for future research.

6.2 Achievements of the objectives

The objectives of this study are stated below:

a. To propose a method to improve the accuracy rate for evaluating a link quality.
b. To develop the proposed method using fuzzy logic to evaluate both hardware-based and software-based metrics.
c. To compare the accuracy rate of the proposed method with methods introduced in other related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI methods).

A method that uses fuzzy logic to evaluate the hardware-based and software-based metrics was proposed to achieve the first objective. To achieve the second objective, the proposed method was developed into a workable prototype using Python, and it consisted of three types of modules — the Fuzzifier module, the Inference module, and the Defuzzifier module. The Fuzzifier module was used to determine the related hardware-based and software-based metrics with their respective membership functions. A set of proposed fuzzy rules that were translated to equations using "and-like" and "or-like" operators were used to calculate the rule output. The Inference module was used to obtain the rule output based on the proposed fuzzy rules and the given input acquired from the Fuzzifier module. The Defuzzifier module was used to aggregate the rule outputs inferred from the Inference module. The result of the Defuzzifier module was used to evaluate the link quality.

To achieve the final objective, a simulation was used to evaluate the accuracy rate of the proposed method and the other related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI method). The simulation results showed that the proposed method had higher accuracy rates than the other related works.

6.3 Contributions

A method that used fuzzy logic to evaluate the hardware-based and software-based metrics was proposed. A set of proposed fuzzy rules that translated to the equation using "and-like" and "or-like" operators were used to calculate the rule output. The results showed that the proposed method produced higher accuracy rates in evaluating the link quality compared to other related works (Triangle Metric, WMEWMA, improved-LQI, effective-SNR, LQE-node and CSI method).

6.4 Future directions

Below are some suggestions for future studies:

i. Bidirectional evaluation

Most recent studies are only focused on the evaluation of the link quality at receiver nodes. However, since communication between sensor nodes is bidirectional, the link quality should ideally be evaluated at both sender nodes and receiver nodes. By doing so, the accuracy rate for evaluating a link quality could be improved.

ii. Integration of the proposed method into the existing routing protocol

The proposed method could be implemented at other layers, for example, the transport layer, to improve the packet transmission rate. The success rate of packet transmission of a routing protocol might be improved if the proposed method is integrated into the existing routing protocol for choosing a better route or next hop to transmit a packet.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

1. Zhirui Huang, Lip Yee Por, Tan Fong Ang, Mohammad Hossein Anisi, & Adam, M. S. Improve the Accuracy Rate of Link Quality Estimation using Fuzzy Logic in Mobile Wireless Sensor Network. *Advances in Fuzzy Systems, 2019,* 1-13. (Published)