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Performance Evaluation of Link Quality Estimation Models for Wireless Sensor Network Using Telosb Sensor Nodes

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ABSTRACT: Radio Links in Wireless Sensor Networks (WSNs) are often unpredictable because the factors that degrade radio signals are significant on the propagation of wireless signals with low power radios. This study evaluates the link quality estimation models for wireless sensor network. Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI), Signal to Noise ratio (SNR) and Packet Reception Rate (PRR) are the parameters considered for the link quality estimation. Experiment was carried out on radio propagation models with specific emphasis on the various parameters of link quality estimation named above. Model equations were developed for all the parameters of link quality estimation using least mean square error method of linear regression analysis. The goodness of fit (R^2) of the link quality estimation models developed was tested and the least value obtained was > 0.66 which confirms a good model. From the model equations developed, the link quality of any environment with related radio characteristics as the test environment would be determined at any given distance using any of the parameters.

KEYWORDS: Radio Links, Link quality estimation models, Wireless Sensor Networks, RSSI, LQI, SNR and PRR

I. INTRODUCTION

The propagation of wireless low-power radio signals such as employed in Wireless Sensor Networks (WSNs) is significantly impacted by several factors that tend to degrade its quality (Nouhaetal, 2011). Consequently, radio links in WSNs are often unpredictable. The quality of radio links of WSNs fluctuates over time (Cerpa, etal, 2005), and space (Zhou, etal. 2006). Factors that lead to link unreliability include the environment, interference and hardware transceivers. Environmental effects are in terms of multipath propagation or background noise. Interference may be due to concurrent transmissions within a wireless network or between collocating wireless networks and other electromagnetic waves. Hardware transceivers may distort sent and received signals owing to their thermal noise (Rappaport, 2001). In WSNs, these radio transceivers transmit low-power signals, which make radiated signals more prone to noise, interference, and multi-path distortion. Also, they rely on antennas with non-ideal radiation patterns, which lead to anisotropic behaviour. Link Quality Estimation (LQE) of WSN is the statistical characterization of low-power links through estimation theory so as to predict the behaviour of the links (Rappaport, 2001). Link quality affects power consumption in wireless transmissions. Link quality is considered at network level while power consumption is considered at node level.

Wireless network behaviour is largely influenced by the performance of the wireless links between the nodes of the network. Performance of a wireless link between a transmitter and receiver is determined by the Radio Frequency (RF) channel between the terminals and the bit-error-performance of their wireless transceivers (Goldsmith, 2005). RF channel models describe the probabilistic relation between link distance and path loss. In any given network, links of same length experience different channel realizations caused by spatial variations due to obstructions and reflections in the scene. As a result, the received signal strength experienced on links of length d is a random variable $P_r(d)$. The RF channel model induces a distribution on $P_r(d)$, where $P_r(d)$ is the received signal strength with distance (d).

Jiang, etal, (2006), stated that the empirical observations on WSN links raised the need for link quality estimation as a fundamental building block for higher layer protocols. Link quality estimation enables these protocols to mitigate and to overcome low-power link unreliability. Link quality estimation in WSNs is a challenging problem due to the lossy and dynamic behaviour of the links, therefore, it is vital to characterize WSN links before designing a routing protocol.

Good routing protocols rely on link quality estimation to improve their efficiency. Also topology control mechanisms rely on link quality estimation to establish stable topologies that resist link quality fluctuations. All these make link quality estimation very important in wireless network.

This work used RSSI, LQI, SNR and PRRs parameters for link quality estimation to determine the Link Quality of a testbed developed at Faculty of Engineering, Nnamdi Azikiwe University, Awka. Experiment was carried out on radio propagation models with specific emphasis on the different parameters of link quality estimation named above. Model equations of the various link quality estimation metrics was developed and tested. From the model equation developed, the link quality of any test environment with related radio characteristics as the developed testbed would be determined at any given distance using any of the parameters.

II. LITERATURE REVIEW

(Yian, Zhitao&Thiemo, 2011) used a software defined radio to develop a number of link quality metrics. The developed metrics were evaluated under several channel conditions and the results obtained showed that the metrics have good accuracy and can handle complicated channel conditions if combined properly.

In (Nnebe&Nwankwo, 2014), a Received Signal Strength Indicator (RSSI) model of an indoor environment was presented using TelosB sensor nodes. In developing this model, an extensive real-time measurement of the RSSI was done for several months; the average of the measurement was taken and used for the development of the RSSI model. Least Mean Square Error (LMSE) method of linear regression analysis was used to develop the model. The result of the analysis showed that the model was good.

In (Carlo, et al, 2014), the triangle metric that would combine geometrically the information of PRR, LQI and SNR into a robust estimator was proposed. The method was to guarantee a fast and reliable assessment of the link quality. The evaluation of this method shows that the triangle metric can identify the quality of links by just employing as few as 10 packet samples; this projects it as an eligible solution for highly mobile sensor network estimation.

Audeoud&Housse, (2018) proposed a two stage classification, in which they considered a very large fraction of links as immediately usable or not. According to them the remaining links need a bit more testing before they are advertised by the routing protocol as good or weak links. Several approaches to link quality estimation were explored but the report was based on the results of experiments on the Grenoble testbed of the FIT IoT-lab which consist of a set of Cortex M3 nodes with IEEE802.15.4 radios. They considered Link Quality Indicator (LQI) metric and the received signal power because LQI gives more accurate information than received signal power which is a poor indication of Packet Delivery Ratio (PDR) that one can expect on a given link,

A performance evaluation of LQI metric in an indoor environment was presented in (Nnebe&Nwankwo, 2019). In this work, a test bed comprising four sensor nodes was developed; one of the sensor nodes functions as the sink while the remaining three others were located at different angles with respect to the sink. Several measured values were obtained at different times; these values were averaged, processed and analysed. Linear Regression Analysis approach was employed in developing the LQI model of the test bed environment. A test of the developed model proved it to be good one and therefore can be employed in any environment with similar radio characteristics.

In Tanakian&Mehrjoo(2019), an adaptive fuzzy filter to balance the stability and agility of LQE by mitigating the transient variation of it was proposed. The proposed fuzzy filter based mainly on Exponentially Weighted Moving Average (EWMA) low-pass filter which its smoothing factor is changed dynamically with fuzzy rules. Adaptive fuzzy and non-adaptive filter was applied to several types of channels from short-term to long-term transitive channels. The filters outputs was compared and result shows that the non-adaptive filter is stable for large values of the smoothing factor and is agile for small values of smoothing factor. The complexity of the proposed adaptive fuzzy filter is low, due to the use of limited number of fuzzy rules and membership functions.

Cerar, et al, (2021) extensively studied link quality estimators developed from empirical data. They analysed Link Quality Estimation (LQE) models that based on Machine Learning (ML) algorithm using performance data. The analysis of the models was done in two perspectives. The first focus was on quality requirements of the applications they serve. Secondly was the analysis of the standard design steps commonly used in the ML community. Existing

open source datasets suitable for LQE research was also surveyed and analysed. They finally developed guidelines for ML based LQE development and dataset collection.

III. PARAMETERS OF LINK QUALITY ESTIMATION

A. Link Quality Indicator (LQI)

Link Quality Indicator (LQI) is a metric introduced in IEEE 802.15.4 which measures the error in an incoming modulation of successfully received packets; it is one of the parameters which can be used to determine link quality of an environment. The LQI metric characterizes the strength and quality of a received packet; measures each successfully received packet and generates an integer value that ranges from (0 – 255), indicating the lowest and the highest quality signals detectable by the receiver. The correlation value of LQI ranges from 50 to 110 where 50 indicates the minimum value and 110 represents the maximum. LQI is calculated by IEEE 802.15.4 transceiver as in (Chipcon, 2005):

$$LQI = (CORR - a).b \quad (1)$$

where $CORR$ is Correlation value, a and b are found empirically based on Packet Error Rate (PER) measurements as a function of the correlation value. The $CORR$ is the raw LQI value which can be obtained from the last byte of the message.

B. Received Signal Strength Indicator (RSSI)

RSSI is another parameter that is used for link quality estimation. Its characteristic shows that the received signal strength decreases with increased distance as shown by Equation 2, (IEEE 802.15.4 Standard. Part 15.4, 2006)

$$RSSI = -(10n \log d + A) \quad (2)$$

Where n is the path loss exponent, d is distance between sender and receiver, and A is the received signal strength at a reference distance.

The idea behind RSSI is that the configured transmitted power, P_t , at the transmitting device directly affects the received power, P_r , at the receiving device. In embedded devices like wireless sensor nodes, the received signal strength is converted to a received signal strength indicator (RSSI) which is defined as a ratio of the received power to the reference power (P_{ref}). Typically, the reference power represents an absolute value of $P_{ref} = 1mW$. An increasing received power results in a rising RSSI.

$$RSSI = 10 \log \frac{P_r}{P_{ref}} dB \quad (3)$$

C. Signal to Noise Ratio (SNR) Estimation

SNR is defined as the ratio of average signal power to average noise power. A high SNR means that the signal is less corrupted by noise and vice versa. SNR can be expressed in dB as

$$SNR_{dB} = 10 \log_{10} SNR \quad (4)$$

SNR is calculated by IEEE standard (Adel, & Norsheila, 2009) as:

$$SNR = P_t - P_L(d) - S_r \quad (5)$$

where P_t is the transmitted power in dBm (maximum is 0dBm for TelosB), S_r is the receiver's sensitivity in dBm (-90 to -94dBm), P_L is the path loss model. Equations 4 and 5 were used to calculate the SNR of the environment under study. For example, the path loss at 1m and 5m are 43.83, 62.60. Therefore, the calculation of the SNR is as shown At 1m



$$SNR = 0 - 43.83 - (-94) = 50.17$$

$$SNR_{dB} = 10 \log_{10} 50.17 = 10 \times 1.7004 = 17.0$$

At 5m

$$SNR = 0 - 62.60 - (-94) = 31.4$$

$$SNR_{dB} = 10 \log_{10} 31.4 = 10 \times 1.4969 = 14.97 \text{ and so on.}$$

D. Packet Reception Rate (PRR)

Packet Reception Rate can also be used to estimate the WSNs link quality. The radio transceiver’s performance can be characterized by representing the Packet Reception Rate (PRR) as a function of the received signal to noise ratio (SNR), y . PRR gives the probability that a packet received with signal-noise-ratio, y will be decoded correctly by the receiver. The relation between packet-reception-rate and SNR depends on the modulation scheme and the packet encoding scheme employed by the radio transceiver. The combination of the environment and radio model can completely describe the link properties observed in a wireless network for low-rate/time division access where interference is not significant. Experiments done by (Srinivasan, et al, 2010) and Analysis done by (Ostfeld, et al., 2008) of low power wireless links have shown that high percentage of network links were either good or bad (<10% and >90% PRR). PRR is either calculated as a decimal or as a percentage.

The PRR for the 802.15.4 wireless physical layer is given (Woehrle, Brockhoff, & Hohm, 2007) as

$$PRR(d) = \left(1 - \frac{1}{2} \exp^{-\frac{y}{2} \times \frac{1}{0.64}} \right)^{8f} \tag{6}$$

where f is the frame size, y is SNR.

IV. RESULT AND DISCUSSIONS

A. Real time measurements were conducted for LQI in the test environment. Data obtained were evaluated and graphs were plotted to show how the quality of the link varies with distance. The Link Quality measured values are compared with the RSSI values with respect to distance to show that the LQI provided by IEEE 802.15.4/ ZigBee transceiver is a true metric for link estimation. Table 1 shows the LQI values against distances measured in the test environment. The LQI of the three sensor nodes and their average against distance are shown in Figure1. The LQI was plotted against distance to show its variation with increase in distance. It was observed that as the distance increases the LQI value decreases with the exception of few deviations which may be due to multipath effect.

Distance (m)	LQI of node ID 301	LQI of node ID 302	LQI of node ID 303	Average LQI of the 3 nodes
1	107.7	107.3	107.6	107.5
5	107.2	107.5	106.9	107.2
10	106.8	107.1	106.9	106.9
15	100.6	106.3	107.5	104.8
20	106.9	106.7	104.6	106.1
25	106.8	107.5	106.8	107.0
30	106.5	95.6	94.7	98.9
35	99.1	95.6	104.2	99.6
40	107.2	93.6	105.1	102.0
45	105.8	97.7	104.8	102.8
50	105.5	83.3	80.7	89.8
55	106.7	100.2	97.3	101.4
60	78.8	78.7	77.1	78.2

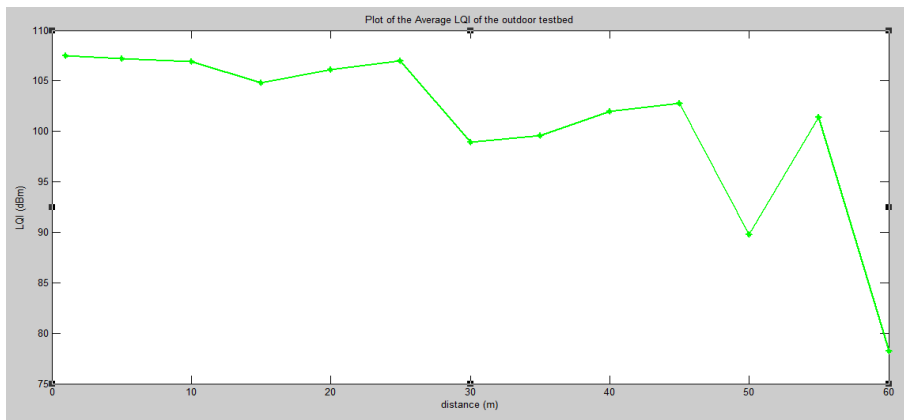


Figure 1: Plot of Average LQI of the 3 nodes against distance

A model equation of LQI of the test environment was developed by finding the least mean square error line of the measured points using the method of linear regression analysis. The plot is shown in Figure 2.

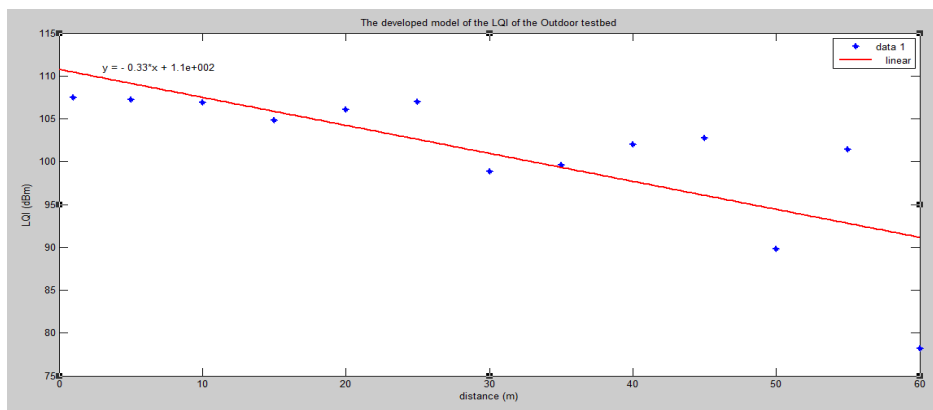


Figure 2: A plot of the LQI model of the testbed

The LQI in the test environment follows the trend given by equation 7.

$$LQI = -0.33 \times d + 110 \tag{7}$$

where d is the distance

The goodness of fit (R^2) of the Link Quality Indicator (LQI) model developed was tested and found to be 0.67. This confirms that the model can generally be applied in LQI determination of an area with similar radio characteristics. Therefore, this equation gives the value of LQI at any distance in the testbed.

B. Table 2 shows the RSSI values of the nodes as are obtained from measurement testbed. Graph was plotted to show the relationship between RSSI and distance of the testbed. It was observed that RSSI decreases as the distance increases, although, there are some exceptions which may be due to line of sight measurements or multipath effects. Figure 3 shows the RSSI of the 3 nodes and its average.



Distance (m)	RSSI (dBm) for node ID 301	RSSI (dBm) for node ID 302	RSSI (dBm) for node ID 303	Average RSSI (dBm) of the 3 nodes
1	-40.7	-46	-44.8	-43.83
5	-61.4	-64.1	-62.3	-62.60
10	-68.1	-69.6	-65.8	-67.83
15	-82.4	-75.9	-74.7	-77.67
20	-80.3	-77.7	-81.9	-79.97
25	-77.6	-88.5	-81.3	-82.47
30	-81.5	-88.5	-89.5	-86.50
35	-88.7	-89.2	-84.7	-87.53
40	-75.8	-88.2	-86.3	-83.40
45	-82.3	-91.8	-85.5	-86.53
50	-84.7	-91.8	-92.2	-89.57
55	-78.8	-88.8	-89.3	-85.63
60	-92.2	-92.43	-92.3	-92.3

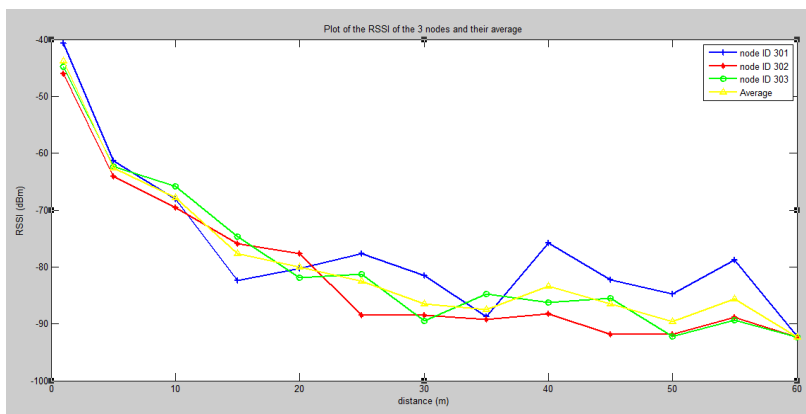


Figure 3: A graph of RSSI of the three nodes and their average against distance

A model equation of RSSI of the testbed was developed by finding the least mean square error line of the measured points. The plot is shown in figure 4.

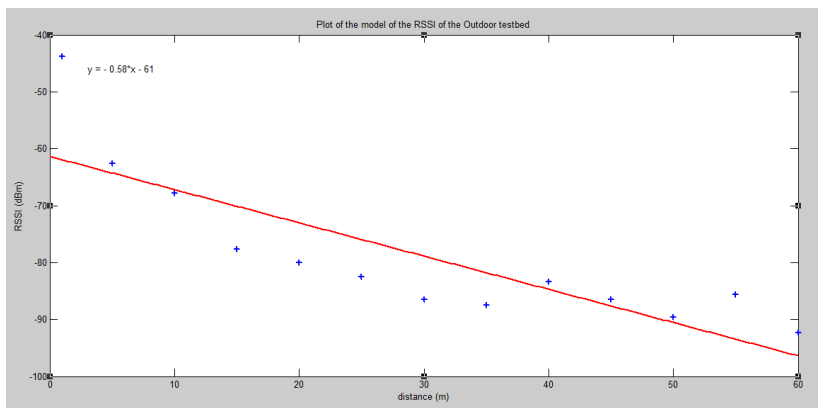


Figure 4: Plot of the developed model of the RSSI of the testbed

The RSSI measurement of the testbed follows the trend given by Equation 8.

$$RSSI = -0.58 \times d - 61 \tag{8}$$

where d is the distance.



The goodness of fit (R^2) of the Received Signal Strength Indicator RSSI model developed was tested and found to be 0.83. This confirms that the model can generally be applied in (RSSI) determination of an environment with similar radio characteristics. Therefore, the RSSI at any known distance can be calculated using the developed model of equation 8 for the testbed.

C. Figure 5 shows the variation of SNR with distance of the testbed. This was plotted using the calculated values as shown in Table 3. A model of the SNR of the testbed was developed as shown in Figure 6.

Distance (m)	Ave. P_L	SNR
1	43.83	17.00
5	62.60	14.97
10	67.83	14.18
15	77.67	12.13
20	79.97	11.47
25	82.47	10.62
30	86.50	8.75
35	87.53	8.11
40	83.40	10.25
45	86.53	8.73
50	89.57	6.46
55	85.63	9.23
60	92.3	2.30

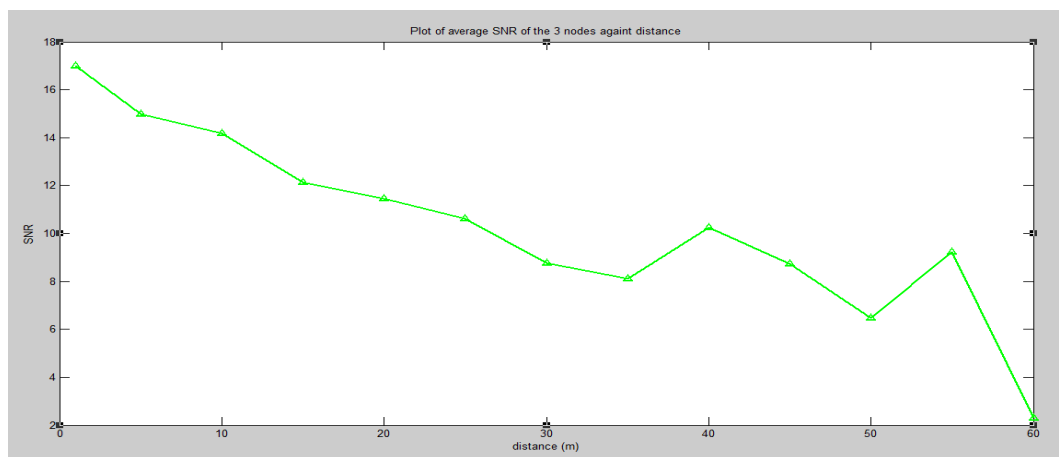


Figure 5: A plot of Average SNR of the nodes against distance of the testbed

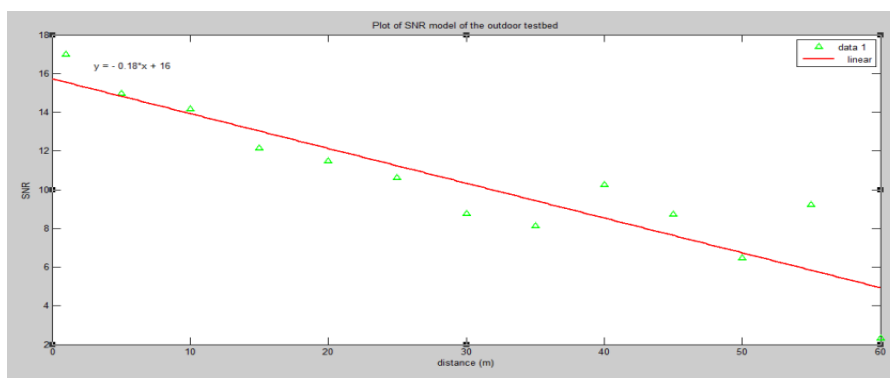


Figure 6: Plot of SNR model of the testbed



The SNR in the test environment as shown in Fig, 6 follows the trend given by Equation 9.

$$SNR = -0.18 \times d + 16 \tag{9}$$

The goodness of fit (R^2) of the Signal to Noise Ratio (SNR) model developed was tested and found to be 0.83. This confirms that the model can generally be applied in SNR determination of an environment with similar radio characteristics. Therefore, the SNR at any known distance can be calculated using the developed model of equation 9 for the testbed.

D.The PRR values calculated from measured values in the testbeds shown in Table 4 and plotted against distance in Figure7.

Table 4: Calculated Link Quality Estimators of the testbed

Distance (m)	Ave. P _L	SNR	PRR	Packet Error Rate (PER)
1	43.83	17.00	1	0
5	62.60	14.97	1	0
10	67.83	14.18	1	0
15	77.67	12.13	1	0
20	79.97	11.47	0.99	0.01
25	82.47	10.62	0.99	0.01
30	86.50	8.75	0.99	0.01
35	87.53	8.11	0.99	0.01
40	83.40	10.25	0.99	0.01
45	86.53	8.73	0.99	0.01
50	89.57	6.46	0.98	0.02
55	85.63	9.23	0.99	0.01
60	92.3	2.30	0.94	0.06

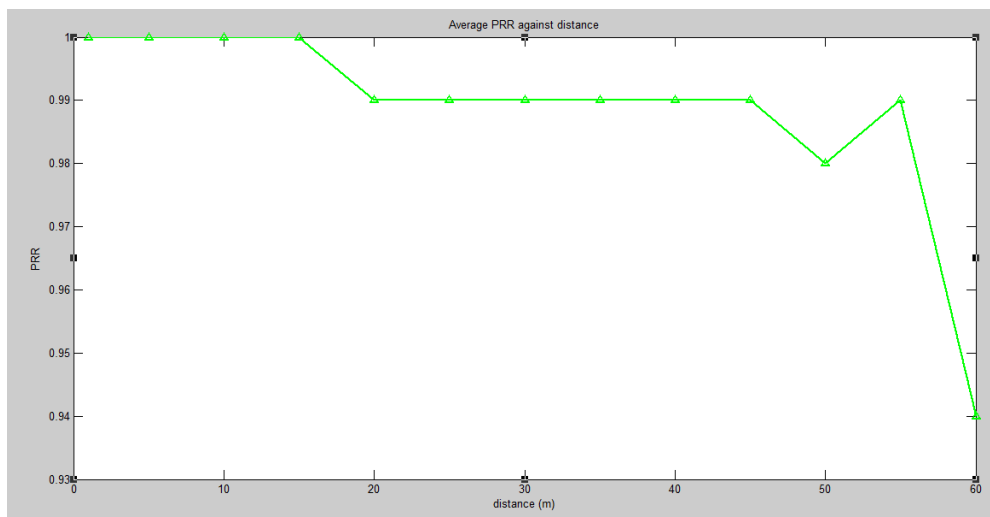


Figure 7: A plot of PRR against distance

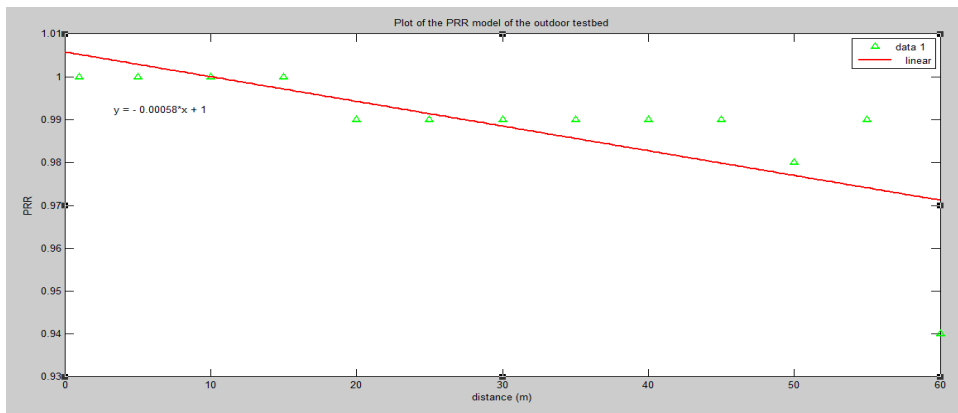


Figure 8: Plot of PRR model

The model equation of the PRR of the testbed developed in Figure 8 is shown in equation 10.

$$PRR = -0.00058 \times d + 1 \tag{10}$$

The goodness of fit (R^2) of the Packet Reception Rate (PRR) model developed for the testbed was tested and found to be 0.71. This confirms that the model can generally be applied in PRR determination of an environment with similar radio characteristics. Therefore, the PRR at any known distance can be calculated using the developed model of equation 10 for the testbed.

E. Packet Error Rate (PER)

Packet Error Rate (PER) of the testbed was calculated as

$$PER = 1 - PRR \tag{11}$$

and the values obtained are shown in Table 4. Fig. 9 shows the plot of PRR and PER against distance.

The plot of PRR and PER in figure 10 shows a graph with negative gradient and inverse variation. It shows that as the PRR increases, the PER decreases till a point where there is no packet loss. The graph of PRR against SNR in figure 11 shows that as the SNR increases, the PRR also increases. At a point PRR appears to be approximately equal to one or 100%. At high LQI, PRR was very high showing that very minimal packet was dropped or that there was no packet loss at all.

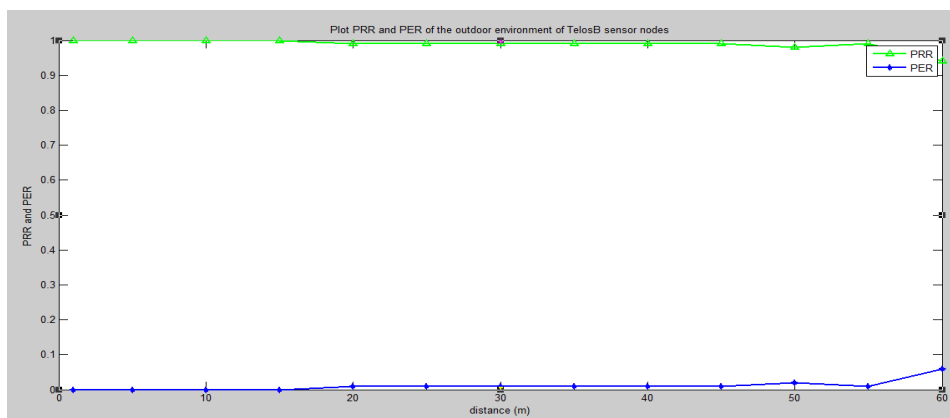


Figure 9: Plot of PRR and PER against distance

Many graphs were plotted to show the relationships of link quality estimation parameters and how they vary with distances and the environment.

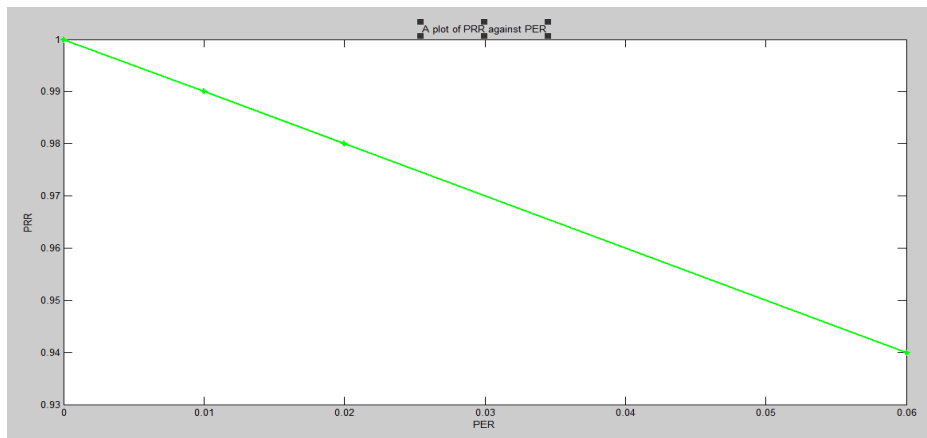


Figure 10: A graph of PRR against PER of the testbed

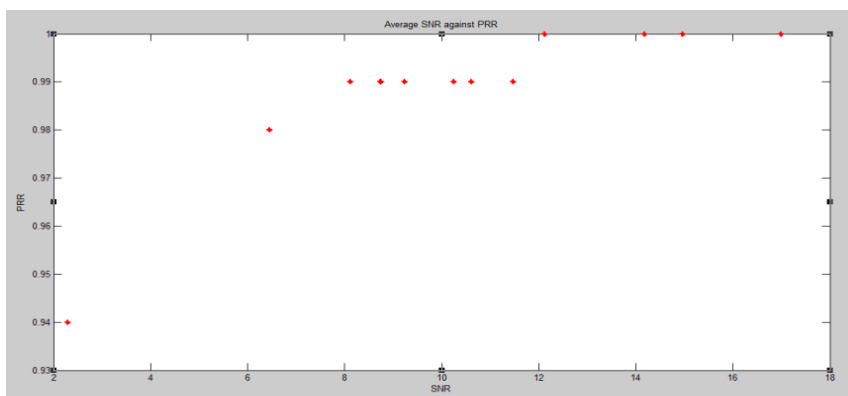


Figure 11: Plot of PRR against SNR of the testbed

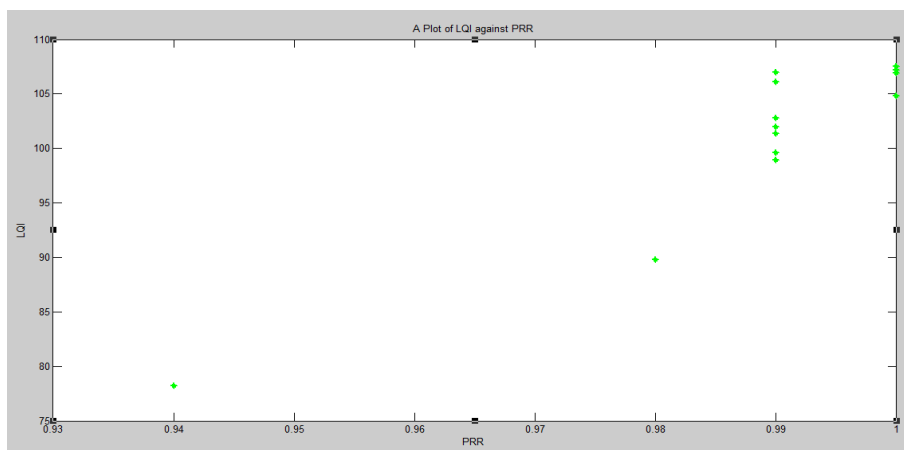


Figure 12: Plot of LQI against PRR of the testbed

V. CONCLUSION

It was observed from the graphs that all the link quality estimators decreases with increase in distance. If links have relatively high RSSI, the corresponding PRR values are all similar and all concentrating around a good value in the proximity of 100%. If the link quality indicator is high the SNR and PRR will also be high and there will be zero or minimal Packet Error Rate (PER).

Based on those four basic observable quantities, the RSSI, LQI, SNR and PRR, it would be inferred that the quality of the link depends on distance and measurement environment. In this experiment, the link is very good having a PRR of approximately 1 (100%). The zero PER implies that there was no packet loss, hence no bit error. Also, PRR of

approximately 1 implies that there was no retransmissions, this is due to the Medium Access Control (MAC) protocol used called Berkeley Medium Access Control (B-MAC) which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The models of the four parameters of link quality estimation was developed and tested and the goodness of fit (R^2) of the models was found to be >0.67 which confirmed that the models can be applied to an environment with similar radio characteristics.

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