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RESEARCH ARTICLE

Development of an Intelligent ZigBee Technique for Improving the Energy Efficiency and Link Quality of a Wireless Sensor Network

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Introduction

ABSTRACT

Wireless Sensor Networks are fixed or moving nodes that senses the environment, communicate the gathered information to a receiver through multiple hops. Unfortunately, wireless sensor network dissipate much energy which is costly to the telecommunications service provider. This research aimed at improving the energy efficiency and link quality in wireless sensor network using an intelligent Zigbee technique. To achieve this objective, the indoor and outdoor environment of Enugu State University of Science and Technology was characterized using four crossbow Telos B sensor nodes, laptop and measuring tapes. A path loss model was developed and the energy consumption characteristics of the environment was determined. The link quality of the characterized environment such as the Received Signal Strength Indicator, Packet Reception Rate and Link Quality Indicator (LQI) was determined using the link quality estimators. Then, an energy efficient routing algorithm for long distance infrastructure monitory was developed and evaluated using Opnet modeler, Castalia and Proteus. Also a smart ZigBee technique was developed to enhance the link quality, maximize the energy longevity of a wireless sensor network. The Network system performance was verified using Simulink. The result showed that the smart ZigBee technique resulted in longer network life time of about 1.8 times that of existing Low energy algorithm consumption hierarchy (LEACH) and 1.25 times of Collection tree algorithm (CTA). Also, its received signal strength threshold was exceptional and it achieved better throughput than LEACH and CTA.

***Keywords:** Wireless Sensor Network, ZigBee Technology, Packet Reception Rate, Link Quality Indicator, Received Signal Strength Indicator, Energy Consumption*

Advances in wireless communications and miniaturization of hardware components have led to the production of sensor nodes which comprises sensing, computing, and communication components integrated on a single board. A wireless sensor network comprises hundreds or thousands of node network that senses its environment, store the information, communicates through wireless channels for information sharing and cooperative processing to the receiver. Even though it senses, collects data, and sends it to a sink through a radio transceiver, it also has the capability of routing those data packets through the neighbors to a sink. It offers various advantages such as reliability, accuracy, and flexibility. The wide range of its application in telecommunication, military environment, health care, and security make wireless sensor networks the fastest growing market in the world but it requires additional growth in its standards and technologies.

A disparaging restraint about wireless sensor networks is that sensor nodes use batteries as a means for lifetime elongation. It is always difficult to change or recharge batteries in the sensors after their exhaustion. This has frustrated the network providers, especially in the high cost of transmission. Some portions of the network can be dead when the batteries of some nodes are drained thereby affecting the reliability and link quality of the network. The high energy consumption in wireless sensor networks is caused by the network topology, poor routing, mobility, retransmission, and node position. Without a proper solution to these problems, the occurrence of frequent signal link breaks, low performance, a slowdown in social communication and networking, the depleted energy level will be seen in the network. There is a need to reform the wireless sensor

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network due to its constraint in power transmission, the processing capacity of sensing data, and redundancy. Low-Energy Adaptive Clustering Hierarchy (LEACH) was proposed for wireless sensor networks. The researcher formed clusters on the sensor nodes and used a Low power consumption algorithm on the sink. This method saved energy and achieved a minimal reduction in energy dissipation. Power-Efficient Gathering in Sensor Information Systems (PEGASIS) & Hierarchical-PEGASIS was presented as an enhancement of LEACH protocol. This development reduced packet delivery time used data aggregation to reduce the number of transmissions and receptions and finally achieved a better performance gain than LEACH. However, it still requires an adjustment in its dynamic topology for a better and more efficient network. A novel data aggregation technique was used to achieve energy efficiency in WSNs. Here, diffusion wavelets for data aggregation and recovery at the sink were used.

An efficient multi-hop routing protocol called Collection Tree Protocol (CTP) was designed for path quality measurement in the wireless sensor network. This was achieved by having a combination of QoF measurements within a node and over the link which immensely determined the intact path quality. A Duty Cycle and Network Coding that uses network coder nodes for transmitting and relay sensors were modeled for forward received data so to improve the lifetime of wireless sensor networks. To an extent, the efficiency was not high and cannot be used in a wireless sensor network. Also, Shah, (2014), an Energy-aware routing protocol was proposed to enlarge the lifetime of the network. Here, the protocol was based on using one out of the multiple paths or selecting a single path randomly from the multiple paths. The single path protocol impeded the ability to recuperate from a path breakdown and also complicated the route setup rendering the whole system inefficient. Heinzelman (2016) presented low energy adaptive clustering hierarchy. It saved little energy and hence cannot be utilized in large areas. This study seeks to improve the high energy efficiency and link quality of a wireless network using modified Zigbee. A modified Zigbee technique is of low cost and low power consumption. Its concept is transmitting data through employing mesh network topology, providing high reliability, a reasonable range, minimizing the energy consumption, and prolonging the lifetime of the sensor nodes. It saves energy using more sleeping time and multi-hopping short range.

2. Literature Review

Conceptual Review

Wireless Sensor Network

Wireless sensor networks are nodes that monitor the environment and cooperatively pass the data to the main location or sink where the data can be observed and analyzed. Wireless Sensor Network has several real-time applications such as event detection, spatial process estimation, environmental monitoring, habitat monitoring, structural monitoring, pipeline monitoring, healthcare positioning and tracking, surveillance of inter-national boundaries for illegal crossing, or smuggling activities, monitoring of roads). Installation of wireless sensor networked system at places where the occurrence of natural disasters such as floods, forest fires, and earthquakes can be averted because the system would respond to changes in the environment in a speedy manner. Sensors in wireless sensor networks have limited and chargeable energy provision. It needs to function unassisted for a prolonged duration of time. Its malfunction can cause great havoc in the network since it can cause topological changes, re-route packets and reorganize the network. Hence, in designing an algorithm for a wireless sensor network, power conservation is very important in a wireless sensor network. Also, the wireless sensor network needs to be fault-tolerant to its functionalities without any interruption or failures such as environmental obstruction, physical damage, or inadequate power supply

ZigBee Technology

ZigBee technology is low cost and low power consumption for equipment that requires battery life for several years. Zigbee supports several network topologies connecting hundreds to thousands of devices. Its protocol support beacon-enabled networks of which its periodic beacons are transmitted to alert other nodes of its presence. It also supports non-beacon-enabled networks in which the receivers are repeatedly active throughout the process. Three types of ZigBee Device Object synchronize in a network namely:

Coordinator - it controls the network by scanning all the channels, starts on the one with low or without activity, and controls how the motes can join or leave the network. It has a collector mote by its side whose function is to receive all the produced data. An external microcontroller is included in the motes which help in processing small data in the system. The coordinator is always powered on for an efficient result.

End- Device - it contains a sensor mote that senses values of phenomena and performs periodic operations of events. When it is not in use, it goes to sleep. Unfortunately, it cannot route packets but can read and send them. Therefore, it cannot act as a relay node, addresses are not the same, and permits raising the network coverage.

Router - here, it receives packets from the sender, routes them to the receiver even if the device addresses are not the same, and permits raising the network coverage.

However, there is a need to control the power of sensor motes by implementing duty cycling in such a way it can be in waking up and sleeping mode to minimize energy consumption. Low Power consumption algorithm can be of help since it can switch between different power modes in sensor mote but it takes into consideration the type of module for better performance.

3. Methodology

Characterization and Development of The Path loss Model of The Environment

The indoor and outdoor environment of Enugu State University of Science and Technology was characterized using four crossbow Telos B sensor nodes, laptops, and measuring tapes. One of the TelesB sensor nodes serving as the sink was connected to the laptop while the other three sensor nodes were placed at 0^0, 90^0, 180^0 at the same distances before the measurement kicked off. TelesB sensor node used TinyOS operating system software of which its four applications used were Make file, Header file, Configuration file, and Module file. The program codes written in NesC were compiled and loaded into the sensor node through the USB port. The nodes were programmed to send data every 5seconds. In the two-Test environments, the humidity in RH, Received Signal Strength Indicator in dBm, light intensity, the temperature, frame size of the data, and Link Quality Indication value were measured against the distance. To completely characterize the propagation path loss model for the WSN, values were established for the following parameters: path loss at a reference distance, $P_L(d_o)$, the measured path loss, P_{Lm}, the predicted path loss P_{Lp}, the path loss exponent, n, and the shadowing factor, X_σ, which is a Gaussian random variable with standard deviation, σ.

$$P_l(dB) = P_l(d_o) + 10nlog\ \frac{d}{d_o} \qquad (1)$$

P_L is the average path loss

The sum of path loss exponent is given as;

$$E(n) = \sum_{i=1}^{k}(P_{Lm} - P_{Lp})^2 \qquad (2)$$

Substituting Equation (1) into Equation (2) yields

$$E(n) = \sum_{i=1}^{k}(P_{Lm} - P_l(d_o) - 10n\log_{10}(\frac{d}{d_o})\ ^2 \qquad (3)$$

Differentiating Equation (2) w.r.t to n gives

$$\frac{\delta E(n)}{\delta n} = -20n\log_{10}(\frac{d}{d_o})\sum_{i=1}^{k}(P_{Lm} - P_l(d_o) - 10n\log_{10}(\frac{d}{d_o}) \qquad (4)$$

Equating $\frac{\delta E(n)}{\delta n}$ to zero and both sides by $-20n\log_{10}$ gives

$$\left(\frac{d}{d_o}\right)\sum_{i=1}^{k}(P_{Lm} - P_l(d_o) - \sum_{i=1}^{k}(10n\log_{10}\left(\frac{d}{d_o}\right)) = 0 \qquad (5)$$

Making the path loss exponent n the subject of formula from Equation (5) gives;

$$n = \frac{P_{Lm} - P_l(d_o)}{\sum_{i=1}^{k}(10n\log_{10}\left(\frac{d}{d_o}\right))} \qquad (6)$$

Determination of the Energy Consumption Characteristics of the Environment Under Study

The power consumption level for the wireless sensor network in linear topology arrangement was achieved through the radio energy model shown in Figure 1.

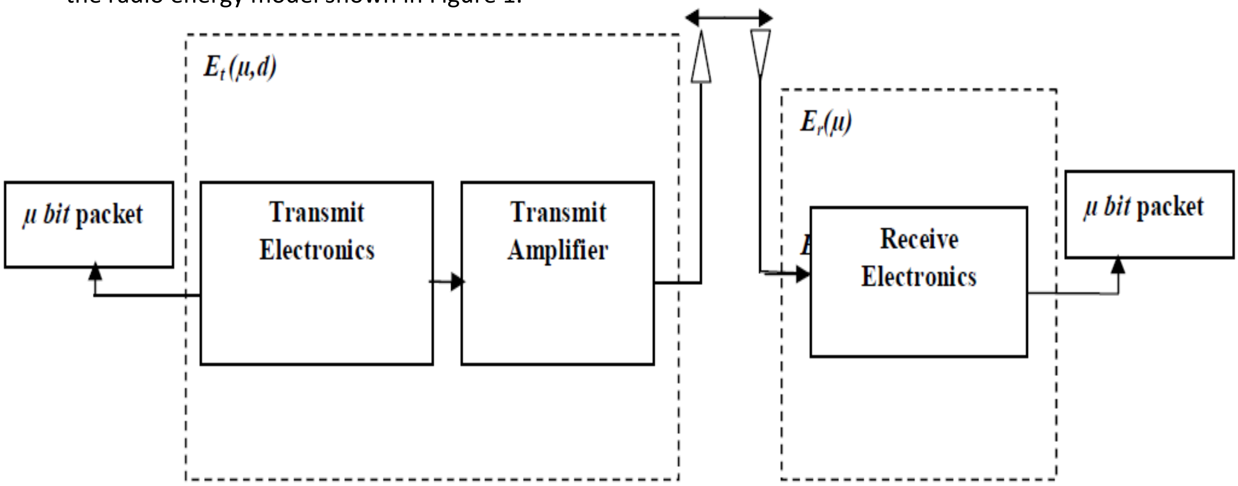

Figure 1: Radio Energy Model Diagram

The source node sends a μ bits message to the sink node through direct hop transmission. 128 bits were transmitted and the following equations were used to evaluate the transmitted and received energy.

$$E_r(d) = \mu\ell_e + \mu\varsigma_{fs}d^2 \quad (7)$$

$$E_t(d) = \mu\ell_e + \mu\varsigma_{fs}d^{2.67} \quad (8)$$

$$E_t(d) = \mu\ell_e + \mu\varsigma_{fs}d^{2.77} \quad (9)$$

$$E_f = 2\mu\ell_e + \mu\varsigma_{fs}d^{2.67} \quad (10)$$

$$E_f = 2\mu\ell_e + \mu\varsigma_{fs}d^{2.77} \quad (11)$$

Where μ denotes the number of bits, ℓ_t and ℓ_r are energy per bit used up by the transmitter and receiver respectively ℓ_e denotes the energy of the electronics, ς_{fs} is the energy dissipated in the amplifier when there is free space or near free space transmission and d is the distance.

Equations (7), (8), and (10) were used to calculate the reception, transmission, and forwarding energies of the first testbed (outdoor), and Equations (7), (9), and (11) were used to calculate the reception, transmission and forwarding energies of the second testbed (indoor). The battery levels of all the sensor nodes in the two testbeds were recorded and the rate of the depletion of each battery was calculated.

Determination of the Link Quality of the Characterized Environment.

This was achieved by carrying out an experiment on radio propagation models with specific emphasis on the variation of Received Signal Strength Indicator (RSS1), Packet Reception Rate (PRR), and Link Quality Indicator (LQI).

Real-time measurements were conducted for LQI versus distance for both testbeds (outdoor and indoor).

The received signal power (P) in dBm was calculated using

$$P = RSSI\_VAL + RSSI\_OFFSET \quad (12)$$

where $RSSI - OFFSET$ is – 45.

The PRR was calculated as

$$PRR(d) = 1 - \frac{1}{2} exp^{(\frac{-y}{2*0.64})^f} \quad (13)$$

Development of an Energy-Efficient Routing Algorithm for long Distance Infrasture Monitoring

An architecture of the Linear Routing Algorithm shown in Figure 2 was developed such that any network that needs to monitor long-distance sensor nodes can be accommodated.

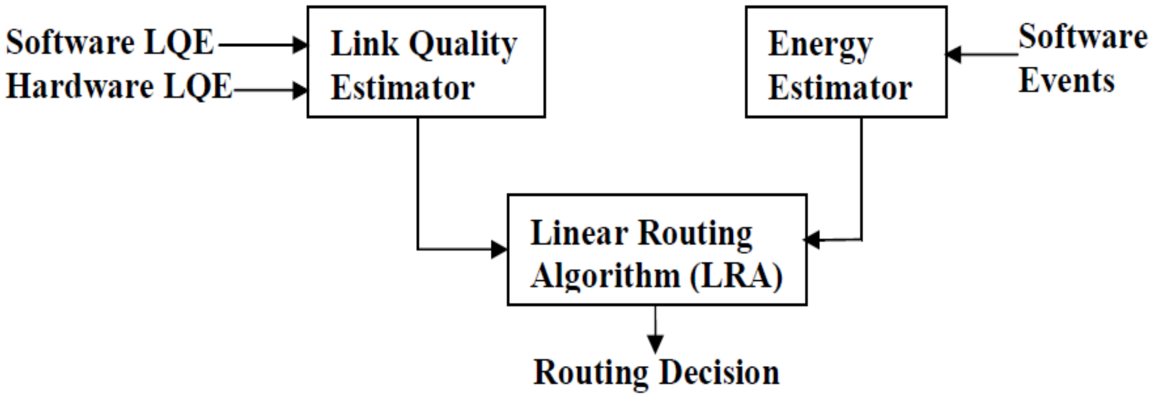

Figure 2: Block diagram Architecture of the Linear Routing Algorithm

The flowchart of the linear routing algorithm is in Figure 3. From the flowchart, the algorithm initialized the update and waited for a predefined period. Thereafter the rank for each of the following matrices: RSSI data, LQI, and neighbor table. Engagement is sent to the neighbor with the best rank when it is accepted. The ID node gets calculated when the engagement sent is accepted. The sensor node sensed the target when it was in fixed linear status, moved with a linear angle when it does not encounter route poison, records received data, and gets updated. Another node was selected and the process continued. The above energy-efficient routing algorithm was implemented. The protocol simulator engines used for simulating the routing algorithm are Castalia 3.2 & Opnet modeler. Proteus 7.6 was also used for a real-time demonstration of the routing algorithm and the energy used by the sensor node was recorded at run time.

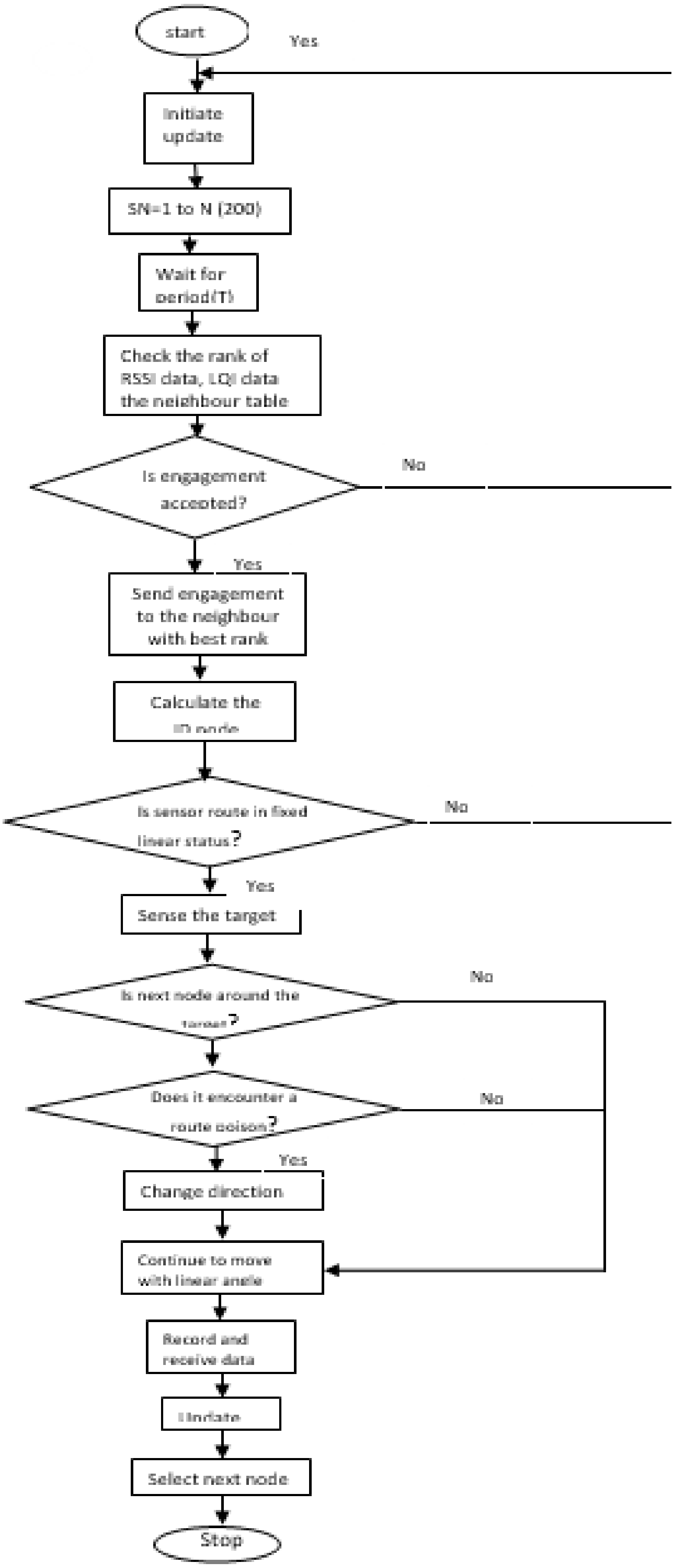

Figure 3: Linear Routing Algorithm Flowchart

Development of a Modified Zigbee Technique

Zigbee Low Power consumption algorithm was developed and implemented in the sensor motes. Its flowchart is in Figure 4. The flowchart shows that when an event is detected, the XB24 module is signaled for wake up. Once it's on active mode, it sends data at a periodic interval. When the battery is low, it turns to the lower power mode, notifying the low battery level and sensor mote. All used devices are initialized and operation continues. Then read the received packets. With this algorithm, XB24 can be turned on and off. 64bytes of data was sent out with various values of operation time and then the energy consumption with or without the Zigbee Low Power consumption algorithm was measured. This was done using the µCurrent device which has a shunt resistor and voltage amplifier. The µCurrent device converts the measured current into a voltage which becomes an input to the ADC of the LPC824 microcontroller. The LPC824 calculates the summation for N measures of the ADC and sends it to the PC through the UART port. The PC saves and displays the result.

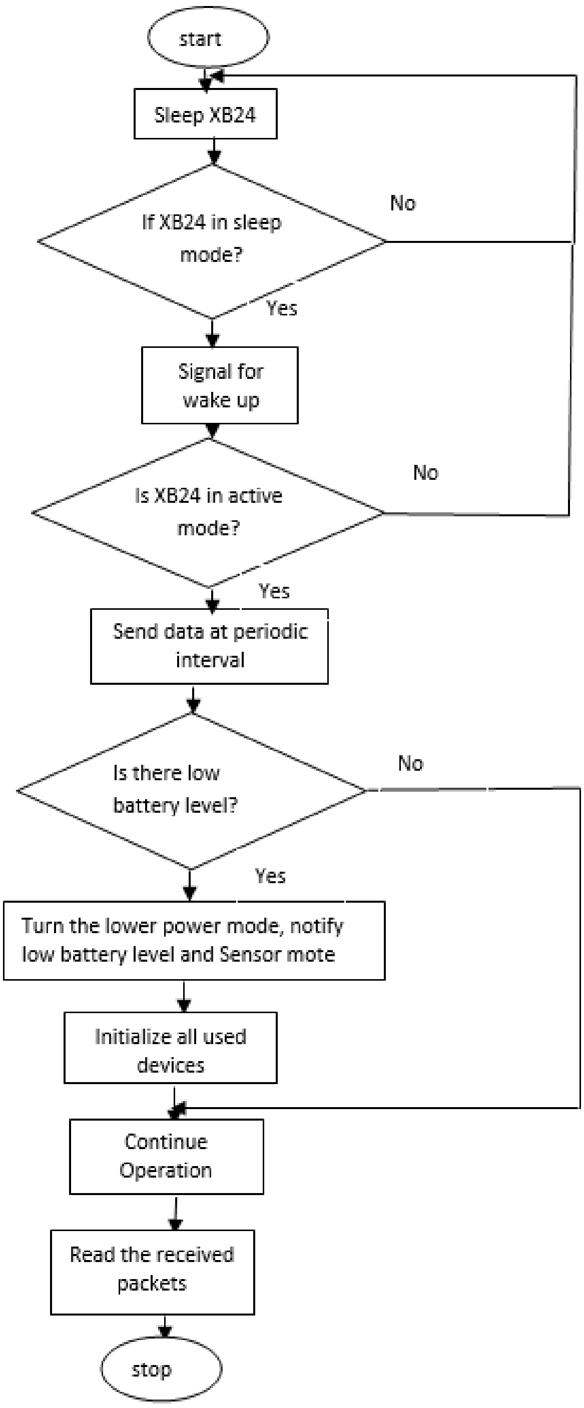

Figure 4: Zigbee Low Power Consumption Algorithm

A computer simulation was used to assess the performance of the developed Linear Routing Algorithm (LRA) and it was compared with Low Energy Adaptive Clustering Hierarchy (LEACH) and Collection Tree Algorithm (CTA).

4. Results

The Received Signal Strength Indicator (RSSI), Link Quality Indication (LQI) value, light intensity, temperature, humidity, and frame size of the data measured against the distance of the test environment were obtained. They were averaged, tabulated, and shown in Table 1.

Table 4.1: Averaged Data of Three Nodes of the Testbed

Distance	Node ID	Voltage (v)	Temp (°c)	Light	Humidity (RH)	RSSI (dBm)	LQI
1	313	2.820	31.06	15.70	66.69	-38.1	107.1
2		2.815	30.38	13.58	68.08	-53.25	106.5
3		2.812	29.97	20.80	69.67	-56.5	107.8
4		2.806	29.36	22.60	71.17	-59.8	107.2
5		2.803	29.30	19.90	70.61	-62.3	106.9
6		2.801	29.09	15.90	70.93	-60.0	107.4
7		2.799	28.99	11.30	71.68	-58.7	107.5

The results were used to evaluate the path loss of the environment of which its plot is shown in Figure 5.

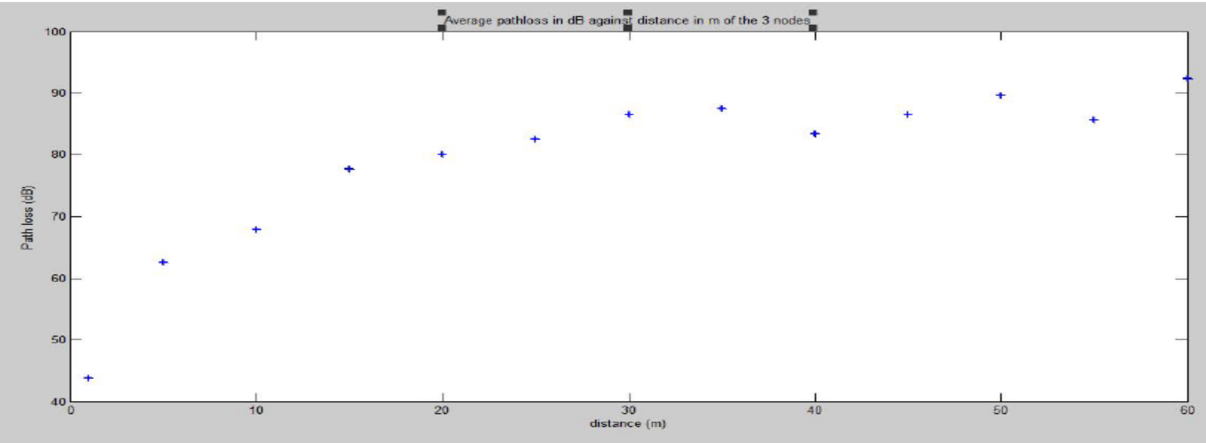

Figure 5: Average Path loss (dB) of the Three Nodes in Outdoor Environment.

It showed that path loss increases when the distance increases.

Then, the plot of the transmitted, forwarded, and received energies for the test environment calculated from the developed energy model is shown in Figure 6.

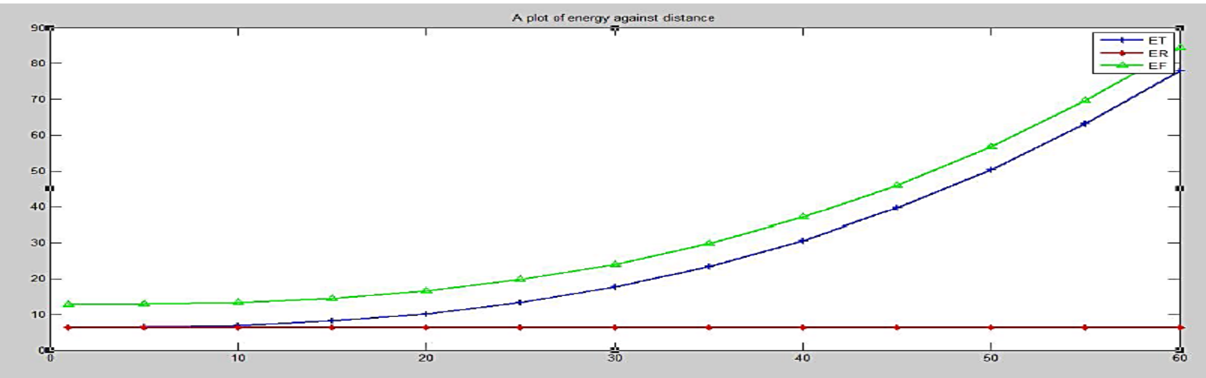

Figure 6: Transmission, Reception and Forwarding Energy of The Testbed Environment

Since the energy dissipated in the receiver is distance independent but depends only on the receiver electronics, the three models at equal distances have the same reception energy. The rate of the depletion of the battery with respect to time is shown in Figure 7.

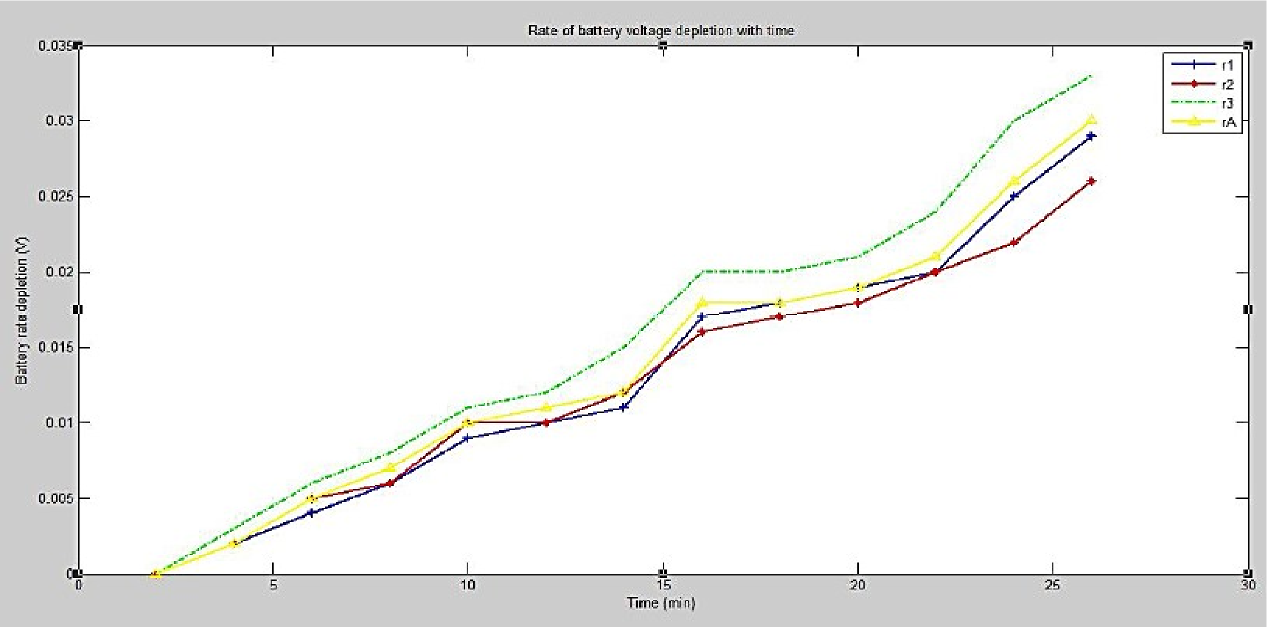

Figure 7: The Rate of Battery Depletion

It shows that as time increases, the battery voltage decreases. Also,

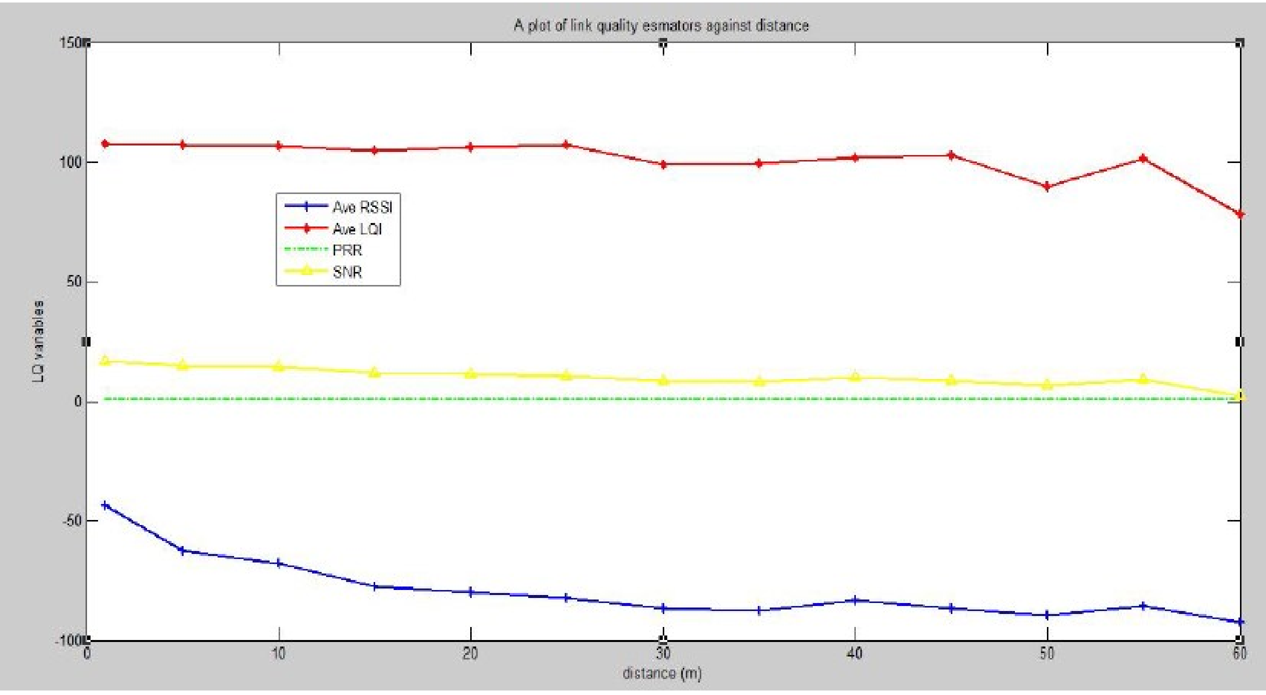

Figure 8: A graph of Link Quality Estimators (RSSI, LQI, PRR, SNR) Against Distance of the Testbed Environment.

It was observed that all the link quality estimators decrease with an increase in distance. If the link quality indicator is high the RSSI, 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 error, hence no bit error. Also, PRR of approximately 1 implies that there were no retransmissions, this is due to the usage of the Berkeley Medium Access Control (B-MAC) protocol.

Zigbee's low Power Consumption Algorithm reduced the energy consumption to a greater height even when the operation time and transmit data interval was long. This can be seen in Figure 9.

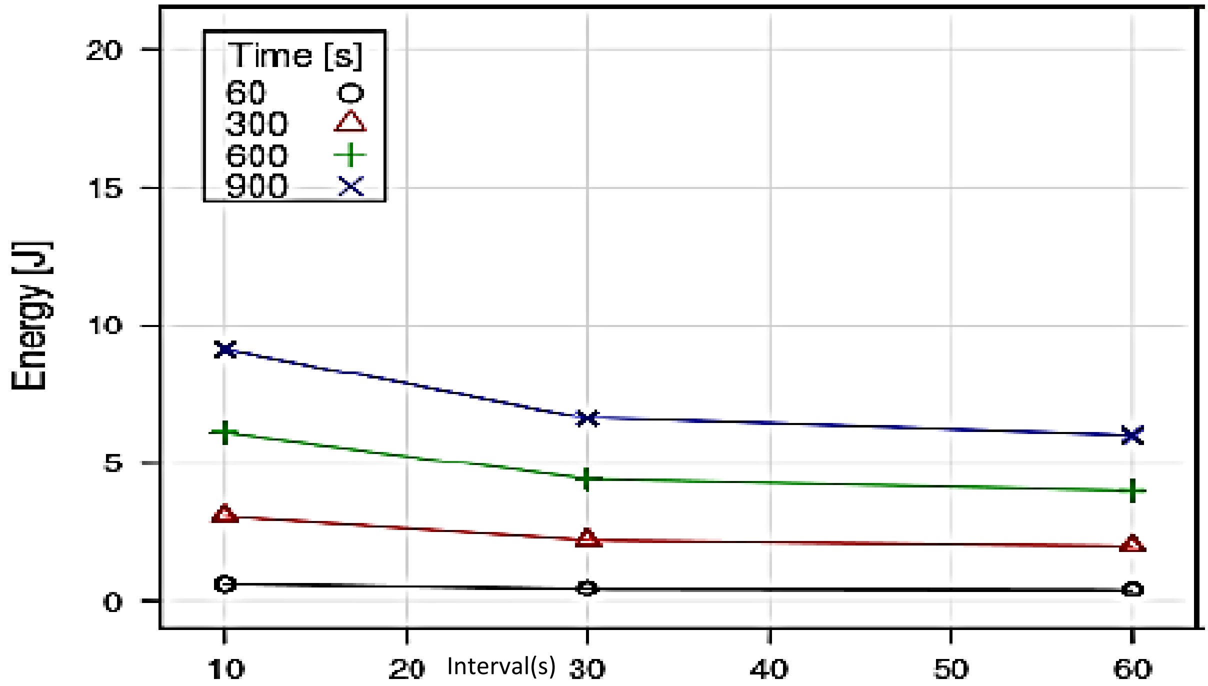

Figure 9: With Low Power Consumption Algorithm

The performance of the Linear routing algorithm of the Zigbee was compared with the existing routing algorithms; LEACH and CTA in terms of a network lifetime and received signal strength. The results are as shown in Figures 10 and 11.

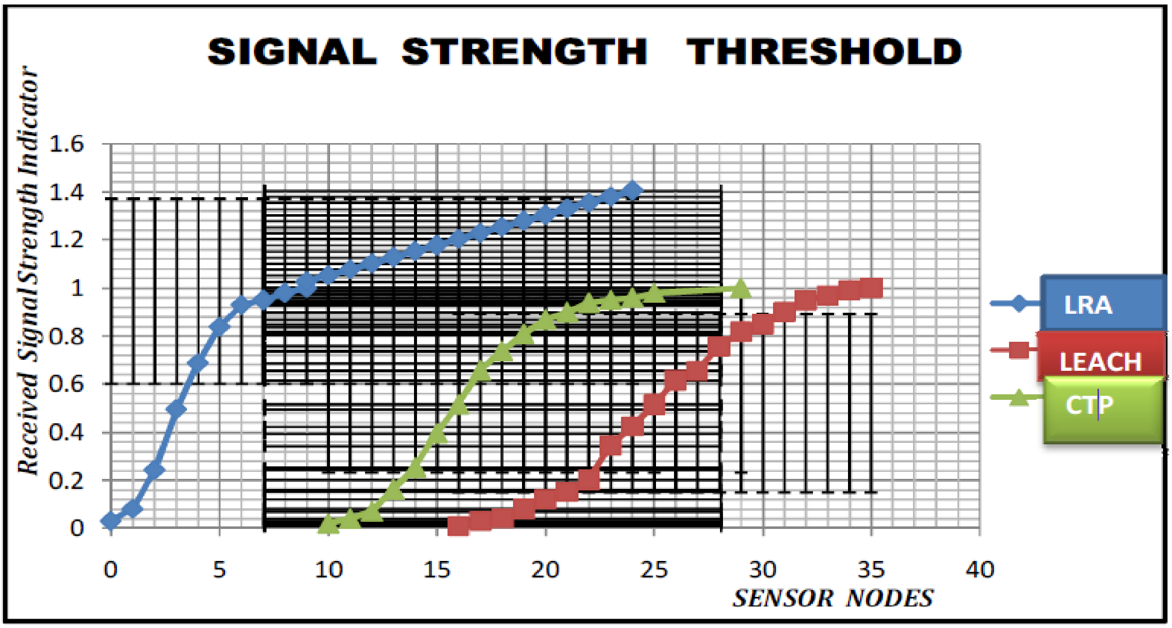

Figure 10: Signal Strength Thresholds of the Algorithms

The plot of the Received Signal Strength Indicator against the number of Sensor in the figure shows that the Signal Strength of the LRA is high compared to LEACH and CTA. The signal strength of LRA is 1.5 times CTA and 4 times that of LEACH. This infers the goodness of the communication link of the system and shows that LRA avoids retransmissions, hence, energy-efficient.

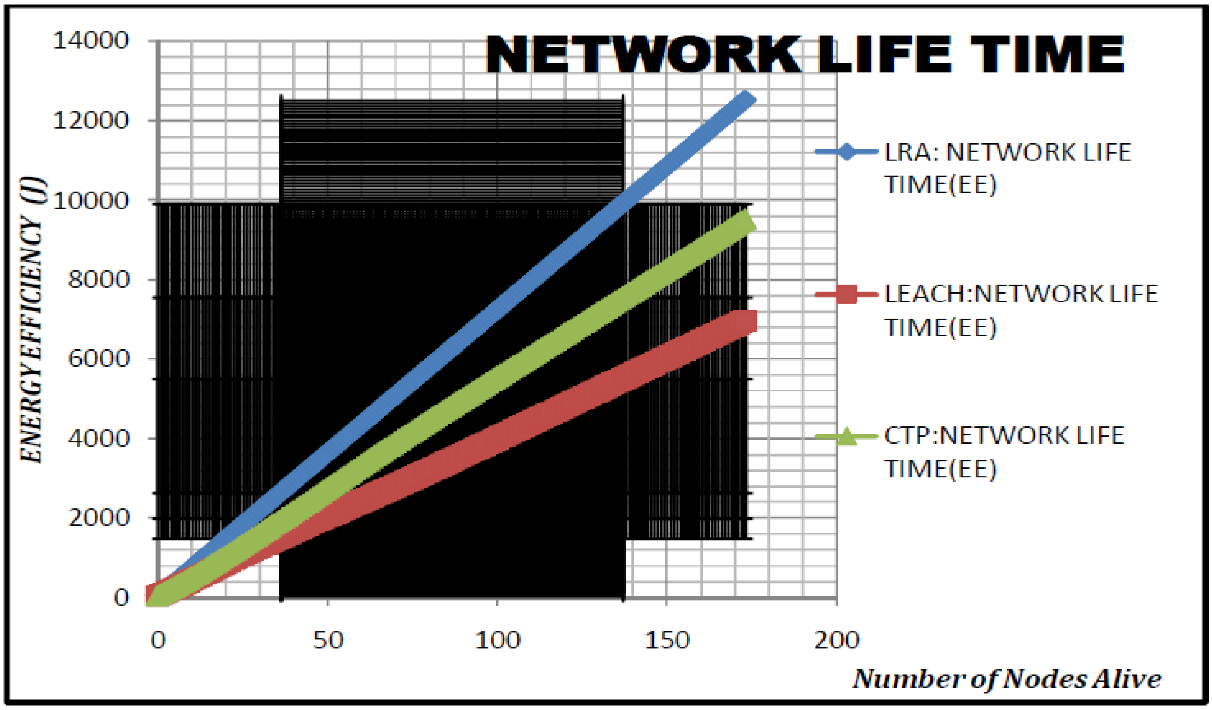

Figure 11: Network Life Time Responses

The plot shows that LRA, in all cases has a higher Network Life Time compared with LEACH and CTA for the sensor nodes deployed. The energy efficiency/ Lifetime of LRA is 1.8 times that of LEACH and 1.25 times that of CTA. LRA delivers most data per unit energy, thereby achieving energy efficiency which improves the network life span.

5. Conclusion

A Linear WSN Routing Algorithm using the modified Zigbee technique was developed. This work presented a Low Power Consumption Algorithm with a duty-cycling mechanism that works on the power mode of the XB24 module and LPC824 microcontroller to mitigate the energy wastage in the wireless sensor network. It showed an 85 percent reduction of the energy consumption of the sensor motes in WSN and when compared with other conventional approaches, there was a significant increase in its power savings. Future research on this work should focus on combining Zigbee's linear routing algorithm and low energy adaptive clustering hierarchy for more improved energy in a wireless sensor network.

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