

Multi-Hop Wireless Sensor Network Performance and Energy Simulation

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ABSTRACT

Simulation of a multi-hop Wireless Sensor Network (WSN) with different topologies and analysis of its performance in terms of number of messages exchanged and energy usage was done in this study. Sensor nodes in the simulation were modelled after an Arduino hardware system equipped with compatible radio transceiver for communication. The sensor nodes were configured in two network topologies, grid and random topology, for performance comparisons. Network sizes varied between 9 nodes and 256 nodes. Simulation was stopped when the communication link between the sensor nodes and their sink node broke down. It was obtained that grid topology has better performance, especially in small network size. Moreover, when the number of nodes in the network is higher, the performance of random topology network exceeds the grid's performance. Nonetheless, the lifetime span of the sensor network does not depend on the networks size or topology, rather on the available energy in each of the sensor nodes. We also have successfully improved the energy consumption model to account for more parameters of radio transceiver used in a WSN node. The energy needed to turn on and off the radio transceiver plays a significant part in the energy consumption of the sensor node.

Keywords: Energy consumption, grid network topology, multi-hop routing, random network topology, wireless sensor network

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INTRODUCTION

General usage of a Wireless Sensor Network (WSN) is for environmental monitoring of a specific area of interest. Researchers need to collect data from sensors that are installed

in the area for a certain time duration (Culler, Estrin, & Srivastava, 2004). Development of Wireless Sensor Network (WSN) has been improved by the presence of alternative smart hardwares like Arduino and Raspberry Pi. It replaces traditional hardware such as Berkeley or Mica motes, especially for general purposes sensor nodes. Arduino offers low-cost, open hardware to researchers in studying WSN and it can be scaled up to hundreds or thousands of nodes at reasonable costs. Before this can be done, however, it is important to create a simulation environment or a simulator for studying sensors network with different sizes, topologies and routing strategies.

Previously, some researchers have done research on a wide range of simulation tools such as WSN to enable researchers to choose the most competent tool for the simulation of WSN and test the proposed research (Nayyar & Singh, 2015). At present, available WSN simulators only supports specific set of hardwares, but simulators with the support of Arduino hardware are not widely available. OMNET++ (<http://www.omnetpp.org>) is a family of libraries that can be used for general network simulation. Castalia, (<http://castalia.npc.nicta.com.au>), made by National ICT of Australia, is a network simulator derived from OMNET++. Meanwhile, TOSSIM (<http://docs.tinyos.net/index.php/TOSSIM>) is a discrete simulator for the sensor network that uses TinyOS for its operating system and Raspberry Pi's based hardware. NS-2 (<http://www.isi.edu/nsnam/ns/>) is a discrete simulator that focuses on network research. However, those simulators do not specifically support WSN. The simulator that supports Arduino-based processors is ATEMU, but the development of this simulator has been stopped by its developers.

Similar research on energy consumption of WSN nodes explored various strategies to achieve better energy usage. Some reports used coloured Petri-Net (CPN) to create power consumption model of WSN and perform energy usage simulation (Dâmaso, Freitas, Rosa, Silva, & Maciel, 2013). Li et al. (2014) proposes an event-driven QPN (Queueing Petri Net)-based modeling technique to simulate the energy behaviors of nodes. Some reports achieved longer network lifetime results by efficiently using available energy, which was obtained by controlling and maintaining the WSN topology (Zabi, Yousuf, & Manikonda, 2014). Meanwhile, some groups described the energy consumption of WSN on various layers of the WSN model (AboZahhad, Farrag, & Ali, 2015). However, while the above strategies utilise multi-hop routing and can be easily implemented in simulations, they are not easy to be applied in a real WSN.

In this research, we proposed a simpler approach to achieve energy efficiency, while maintaining the degree of applicability low by using decision-tree-based multi-hop routing strategy and Dijkstra algorithm to determine the shortest path. In order to determine the energy consumption of WSN, the calculation used is as presented in the previous work of AboZahhad et al. (2015).

In our previous research, the characteristics of SiGe-based nanoelectric devices were simulated as supporting the WSN's system (Hasanah, Abdullah, & Winata, 2008; Hasanah, Noor, Jung, & Khairurrijal, 2013). In this research, the simulation of a multi-hop Wireless Sensor Network with different topologies and analysis of its performance were done in terms of the number of messages exchanged and energy usage. To perform the simulation, a new

WSN simulator that supports hardware was developed using the Matlab programming tool. The simulator supports specific parameters derived from Arduino's electrical characteristics, network topologies, and multi-hop routing strategy. The sensor nodes in the simulation were modelled after the Arduino hardware system which was equipped with a compatible radio transceiver for communication. Meanwhile, the multi-hop routing strategy was employed and messages exchanged between nodes were counted. In addition, energy used by the sensor node to send and receive message was calculated. Using these data, the performance and energy usage of the WSN network can therefore be assessed.

METHODS

Multi-hop Routing

In general WSN application, each sensor node is equipped with limited energy source like small battery. Using continuous energy supply is not practical for WSN application, except for the sensor node that acts as a collector for data sent by all other nodes in the network, or which is usually called sink node. Due to this energy limitation, the sensor nodes have to be smart enough to manage its energy usage during normal operation with proper routing strategy.

Routing is a process of finding the optimum way delivering data from a start point to the destination. There are several protocols that can be used for routing such as LEACH, HEED, PEGASIS, TEEN, and APTEEN (Milan & Moravek, 2011). Routing with LEACH and HEED is usually considered as single-hop routing. One disadvantage with single-hop routing is that when the distance between the nodes increases, the energy needed to send data to other nodes increases significantly (Biradar, Sawant, Mudholkar & Patil, 2011; Farooq, Dogar, & Shah, 2012).

In this simulation, multi-hop routing was realised using tree-based routing (Milan & Moravek, 2011). This routing is a simplified way of general M-LEACH routing protocol, where a group head node or base station node was chosen prior to simulation. In this routing scheme, a sensor node sends message to the base station node through a series of neighbour nodes. A node can relay several messages from its neighbour nodes, which consumes more energy.

The simulation used Dijkstra algorithm in determining the closest distance between nodes in a graph structure. This algorithm was implemented in Matlab by grTheory toolbox. Then, it was used to develop our simulation software.

Energy Consumption Model

After the routes from every node to base station nodes are clearly defined, the number of messages processed by each node can then be calculated (Milan & Moravek, 2011). In Figure 1, node n_1 sends data to the next nodes until node n_4 . Node n_2 receives the data, performs checking on route information, and then sends the data to node n_3 . Sensor nodes use omnidirectional antenna for radio communication, so the same data sent by n_2 are also received (overhear) by n_1 . By node n_1 , the received message is ignored because the data are not intended for n_1 .

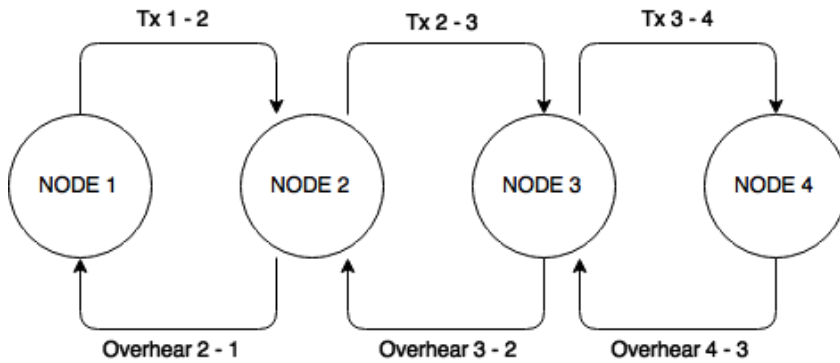


Figure 1. Data Transmission Diagram

Thus, node n_1 uses energy to send the initial message E_{TX} and energy E_{RX} to receive overheard message from n_2 . The energy used by n_1 is:

$$E_{n1} = E_{TX} + E_{RX} \tag{1}$$

As relay nodes, n_2 and n_3 use energy E_{RX} to receive messages from the previous node, E_{TX} , to send the relayed message, and E_{RX} to receive overheard message. Thus, energy used by relay nodes is:

$$E_{nr} = E_{TX} + 2E_{RX} \tag{2}$$

The last node n_4 as base station node is only responsible for receiving messages, so the energy used is equal to E_{RX} .

$$E_{SB} = E_{RX} \tag{3}$$

Energy consumption for a sensor node is defined as (AboZahhad et al., 2015):

$$E_{tran} = P_{ont}T_{ont} + P_{onr}T_{onr} + P_{tr}T_{tr} + P_{sm}T_{sm} + P_{dc}T_{on} \tag{4}$$

where the total time duration is divided between the communication active mode T_{on} , transient mode T_{tr} and sleep mode T_{sm} . During sleep mode, the leaking current of switching transistors dominates the power consumption P_{sm} . This term is often neglected, i.e. P_{sm} can be set to zero. The transient-mode time arises mainly from the frequency synthesiser settling time, and the settling time for other devices such as a mixer and power amplifier can be neglected and power consumption at this mode is P_{tr} . During the active mode, power is consumed at digital circuits (P_{dc}), analog circuits at the transmitter (P_{ont}) and receiver side (P_{onr}). P_{dc} is usually neglected

because power consumption of a digital signal processing is relatively small compared to that of the analogue circuits, especially in a wireless radio application. Equation (4) then can be simplified as follows:

$$E_{\text{tran}} = P_{\text{ont}}T_{\text{ont}} + P_{\text{onr}}T_{\text{onr}} + P_{\text{tr}}T_{\text{tr}} \quad (5)$$

Note that in Equation (5), every sensor node is treated equal so that its energy consumption is calculated by adding the energy needed to transmit and receive radio, as well as the energy needed by radio transceiver during settling time (time needed to change from standby state to working state).

In our research, we expanded equation (5) by treating sensor node depending on its function during the operation of WSN. For the sensor node that only transmits messages as shown by Node 1 in Figure 1, its energy consumption is defined by equation (1). E_{TX} and E_{RX} can be defined as:

$$E_{\text{TX}} = P_{\text{ont}}T_{\text{ont}} + P_{\text{tr}}T_{\text{tr}} + P_{\text{tr,down}}T_{\text{tr,down}} \quad (6)$$

$$E_{\text{RX}} = P_{\text{onr}}T_{\text{onr}} + P_{\text{tr}}T_{\text{tr}} + P_{\text{tr,down}}T_{\text{tr,down}} \quad (7)$$

Where $T_{\text{tr,down}}$ is the time needed by the transceiver system to change from transmit/receive state to standby state. By using equation (6) and (7) into equation (1), we can obtain:

$$E_{\text{tran,source}} = P_{\text{ont}}T_{\text{ont}} + P_{\text{onr}}T_{\text{onr}} + 2(P_{\text{tr}}T_{\text{tr}} + P_{\text{tr,down}}T_{\text{tr,down}}) \quad (8)$$

Using the same approach, equation (2) for relay node can be expanded into:

$$E_{\text{tran,relay}} = P_{\text{ont}}T_{\text{ont}} + 2P_{\text{onr}}T_{\text{onr}} + 3(P_{\text{tr}}T_{\text{tr}} + P_{\text{tr,down}}T_{\text{tr,down}}) \quad (9)$$

And finally, equation (3) will change into:

$$E_{\text{tran,BS}} = P_{\text{onr}}T_{\text{onr}} + P_{\text{tr}}T_{\text{tr}} + P_{\text{tr,down}}T_{\text{tr,down}} \quad (10)$$

By using equations (7), (8), (9), we developed a WSN simulator using MATLAB to investigate a sensor node's energy consumption. By differentiating sensor node's functions as a source, relay, and base station node, we can learn more about how energy consumption varies between nodes in a WSN.

Hardware used to build sensor node is Arduino Uno R3 with nRF24L01 radio transceiver module. In this simulation, energy consumption by Arduino is not included in the calculation because its value is the same for all the sensor nodes. The simulation focuses on the energy used for data communication between the nodes. Important parameters from nRF24L01 radio transceiver model were obtained from its factory datasheet, as shown in Table 1. The important parameters are electrical current needed for transmitting data at 11,3 mA, receiving data at

11,8 mA, and for standby at 22 uA. Meanwhile, the time needed to change between standby state to ready-to-transmit state and ready-to-receive data is 130 uS (micro seconds), and the same value for the opposite state changes. Other important parameter is data transfer rate of the radio transceiver, which is at 1 Mbps (Milan & Moravek, 2011).

Table 1
nRF24L01 radio transceiver parameters according to factory datasheets

Parameter	Value
T_{tr}	130 μ S
$T_{tr,down}$	130 μ S
$I_{tr,receive}$	8.3 mA
$I_{tr,down,receive}$	8.3 mA
$I_{tr,transmit}$	8.0 mA
$I_{tr,down,transmit}$	8.0 mA
I_{onr}	11.8 mA
I_{ont}	11.3 mA
$T_{onr} = T_{ont}$	0.4 mS
I_{rxtx}	8.0 mA
T_{rxtx}	130 μ S

Length of data message sent by every sensor nodes was assumed to be similar to the length calculated by some reports (Milan & Moravek, 2011). In IEEE 802.15.4 protocol, data payload length is 30 bytes. Sensor reading data are stored in this data payload. Additional information added into the message is Data Request message at 12 bytes length, while ACK message used as communication control at 5 bytes length. Thus, the total length of data messages is 47 bytes.

Simulation Scope

Simulation software was created using Matlab. For every network topology used, network size or the number of sensor nodes in the network varies according to n^2 , where $n=3, 4, \dots, 16$ nodes. The software will create the network and assign all possible communication links between each node. The software assigns which node will act as base station node.

Area where the network resides was assumed to be 500 m wide and 500 m length. Nodes are placed algorithmically in the area according to the chosen topology. Nodes are placed in various points in the Cartesian coordinate which has its zero or centre point in the bottom left corner of the area.

Each sensor node was assumed to have 1 Joule of energy at the beginning of the simulation, except for base station node. Base station node has much more energy to prevent it from running out of energy. The next assumption is that Arduino's energy consumption is not included in the simulation.

RESULTS AND DISCUSSION

Network Performance Analysis

Simulation was run until all nodes that positioned at 1 hop before the base station node had run out of its energy. All messages sent, relayed and received by every node were recorded for further analysis. Figure 2 shows the simulation result for network with 9 sensor nodes.

For random topology in Figure 2, if node 5 is assigned as base station node, then nodes 2, 3, 4, and 9 are positioned at 1 hop before node 5. If all four of those nodes died, the simulation would stop. Similar rules applied to the grid topology in Figure 2.

As shown in Figure 2, the simulation stopped because all the sensor nodes in the network became dead at the same time. For comparison, on another simulation run with 9 sensor nodes and random topology with different nodes position, the simulation stopped when all the nodes positioned at 1 hop before the base station nodes died, as shown in Figure 3.

In Figures 3, nodes 2 and 3 died earlier than other nodes, which caused the simulation to be stopped at 113th run. Here, it could be seen that sensor nodes placement in the networks is very important to maximise the lifetime of the WSN network.

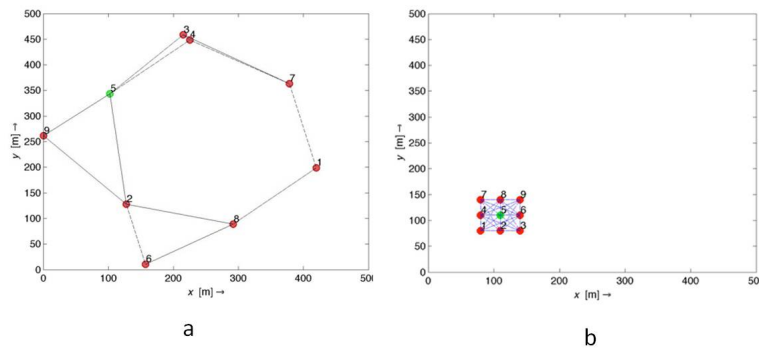


Figure 2. Random Topology (a) and Grid Topology (b) Every node is labeled with number. Both graph axes represent distance in metres. Red nodes represent dead node. Green nodes represent base station nodes

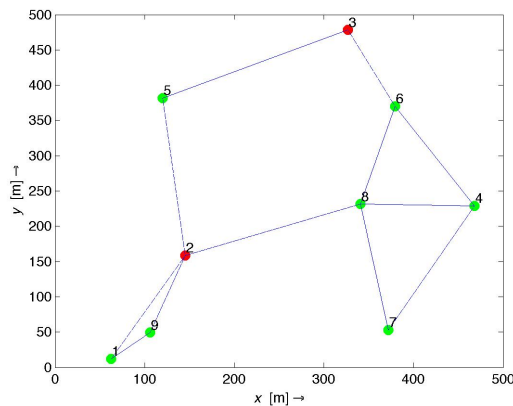


Figure 3. Simulation stopped because nodes 2 and 3 had run out of energy, closing the route to base station node 5

For network with random topology and 9 nodes, the simulation stopped at 222nd run. Grid topology had the same number of run as well. The difference between random and grid topology, however, is clearly shown in Figure 4.

It can be seen from Figure 4(a) that in random topology, nodes died gradually from the 100th run until 222nd run, whereby 6 nodes died at the same time. Different cases happened to the grid topology, where all 9 nodes died at the same time at 222nd run, as shown in Figure 4(b). This can be explained as follows. In the grid topology with 9 nodes, 8 nodes were placed at 1 hop before the base station node, as shown in Figure 2. Energy used by the 8 nodes is calculated using Equation (2). However, for the random topology shown in Figure 2, less number of nodes is placed at 1 hop before the base station node. These nodes act as relay nodes, in which the energy usage is calculated using Equation (3). The energy used for relaying messages is higher than energy used for sending messages, so relay nodes in random topology will run out of energy sooner than other nodes. The same pattern was also found to happen to network with higher number of nodes, with few differences.

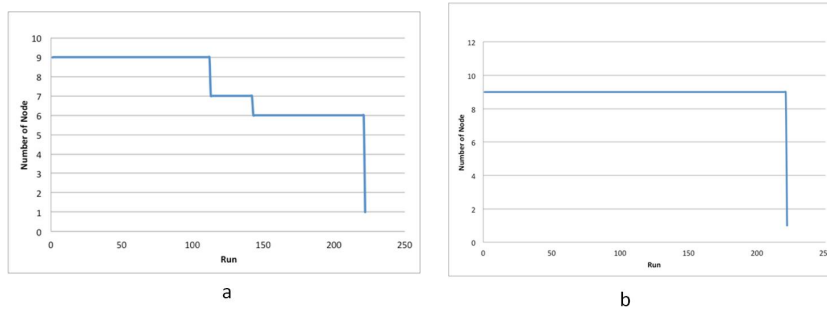


Figure 4. (a) Number of alive nodes at each simulation run for random topology with 9 nodes, and (b) number of alive nodes at each simulation run for the grid topology with 9 nodes

In Figure 5, for the random topology with 144 nodes, it can be seen that from around 140th run until 222nd run when the simulation stopped at the 82 run, there were around 80 nodes still up and running. These nodes were still sending messages, but they could not reach the base station node because there were no routes available.

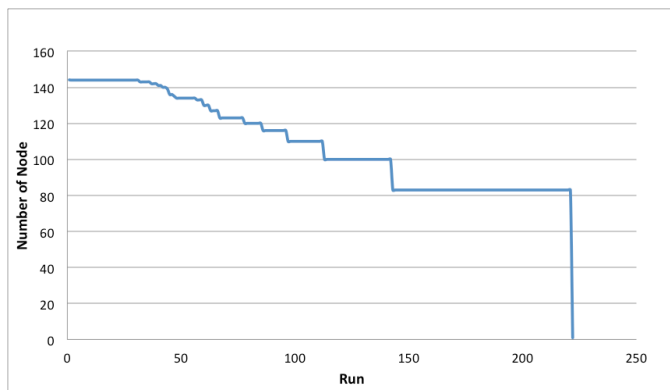


Figure 5. Number of alive nodes at each simulation run for the random topology with 144 nodes

In Figure 6, for the grid topology with 144 nodes, it can be seen that from around 140th run until 222nd run when the simulation stopped, there were only 60 nodes still up and running, which is lower compared to 80 nodes for the random topology. The WSN network with random topology seems to have advantage especially for a large number of sensor nodes compared to the grid topology network.

Interestingly, simulation stopped at the same run, i.e. 222nd run, for both the random and grid topology and was not affected by the number of nodes in the network. Using this fact, it can be concluded that the lifetime of the WSN network does not depend on the size of the network and topology, but rather determined by the available energy in each sensor nodes.

From Figure 4 through Figure 6 above, we can analyse which topology performs better than the other. As stated before, the criterion to stop the simulation is if there is no more possible route to go from the sensor node to the base-station node, this is because all the nodes positioned 1 hop before base-station node are run out of energy. Thus, we can calculate the number of messages sent by sensor nodes and received by base-station node. The topology with a higher number of received messages by base-station node for all simulation runs is the best topology. Table 2 shows the number of messages received by the base-station node.

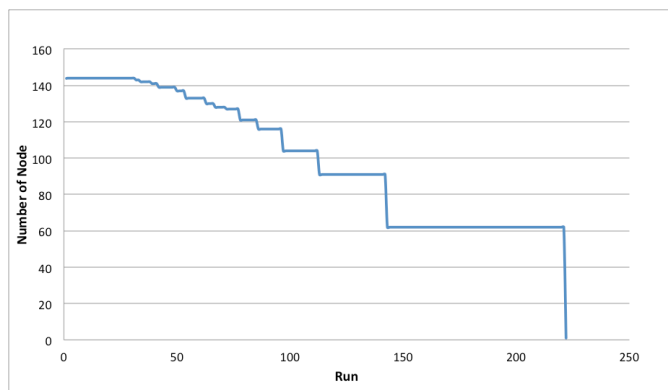


Figure 6. Number of alive nodes at each simulation run for grid topology with 144 nodes

From Table 2, it is clear that with higher number of nodes in a WSN, there are more messages received by the base-station node. In the grid topology, the number of messages received by base-station node is higher than in the Random topology, except for the number of sensor nodes above 144. This is because in a network with more than 144 nodes and with the same area size, more nodes using the same routes cause the intermediate nodes to run out energy quickly, especially in the grid topology. However, if we calculate the average of received messages compared to the number of nodes available in the WSN (Table 2), then what we can obtain for the same topology is that the number of messages per node is almost identical regardless of the number of nodes in the WSN. In the random topology, the average number of messages/node is 167 messages/node, whereas the average number is 184 messages/node in the grid topology. We summarised these in Figure 7.

Table 2
Number of messages received by the base-station node for Random and Grid topology

Number of Nodes	Topology					
	Random			Grid		
	Number of Message	Run	Message/Node	Number of Message	Run	Message/Node
9	1479	222	164.33	1776	222	197.33
16	2630	222	164.38	3172	222	198.25
25	4435	222	177.40	5012	222	200.48
36	5896	222	163.78	6874	222	190.94
49	8463	222	172.71	9904	222	202.12
64	10962	222	171.28	11354	222	177.41
81	13501	222	166.68	14721	222	181.74
100	16337	222	163.37	16766	222	167.66
121	19826	222	163.85	20658	222	170.73
144	24044	222	166.97	22120	222	153.61
169	26285	222	155.53	26866	222	158.97
196	30928	222	157.80	29267	222	149.32
225	35729	222	158.80	34044	222	151.31
256	40494	222	158.18	35772	222	139.73

From Figure 7, it can be seen that the smaller number of sensor nodes, the higher the number of messages/node for grid topology compared to the random topology. As shown in Figure 7, however, the graph for grid topology has a significant and sudden decreasing pattern than that of the random topology, and for the number of nodes above 200, the graph for the grid topology is lower than the random topology. We can also see in Figure 7 that the graph for random topology is more consistent compared to the grid topology for all range of the number of nodes.

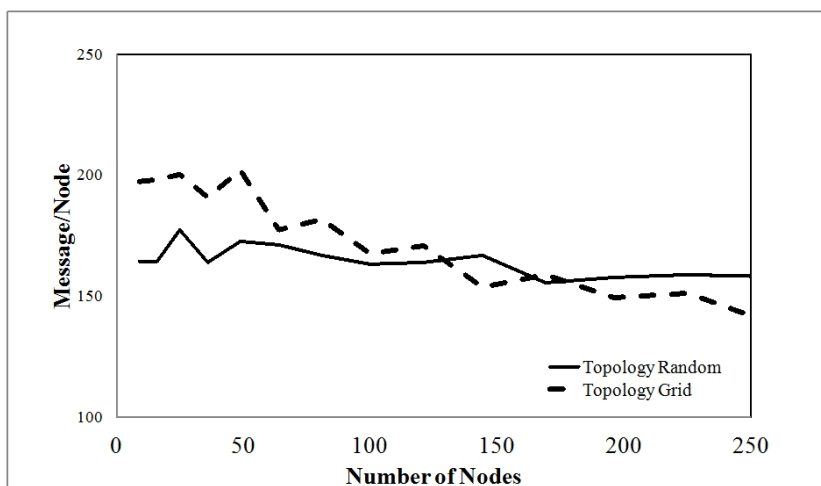


Figure 7. Number of messages per node in Random (blue line) and Grid (red line) topology

Energy Consumption Analysis

For the network with random topology and 9 nodes, simulation stopped at 222nd round. The energy consumed by each nodes during the whole run, calculated using Equation (5), (9), (10), and (11) above, was recorded and plotted. For a source node with energy consumption defined in Equation (9), the energy consumption $E_{\text{tran,source}}$ compared to E_{tran} calculated using Equation (5) is shown in Figure 8.

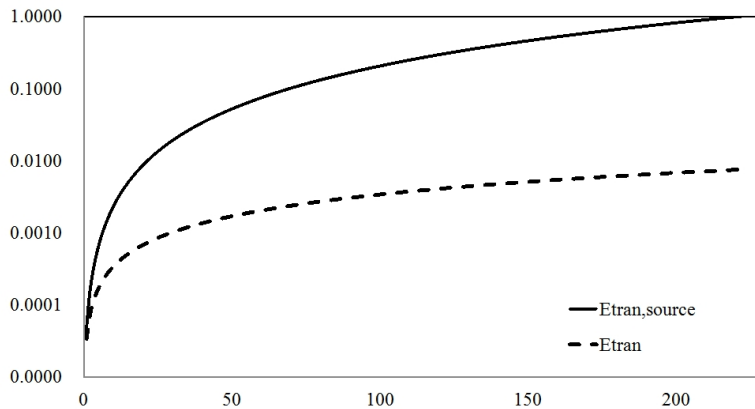


Figure 8. Energy consumption of a source node. Energy use shown is in the logarithmic scale

It can be seen from Figure 8 that the energy consumption for a source node in our simulation differs greatly from the energy consumption calculated in Milan and Moravek (2011). The difference comes from the additional term of $P_{\text{tr,down}}T_{\text{tr,down}}$ introduced in Equation (9) as compared to the terms used Equation (2) above. The added term represents energy needed by the transceiver chip to go from the working state (transmit or receive state) to standby state, or in other words, to sleep. $P_{\text{tr}}T_{\text{tr}}$ represents the energy needed to go from the standby state to working state or to wake up state.

For relay node shown in Figure 9, the difference between $E_{\text{tran,relay}}$ and E_{tran} become more significant. $E_{\text{tran,relay}}$ shown in Equation (10) uses more energy to receive messages and to wake up and sleep. Relay nodes process more messages compared to source node. It needs to wake up to receive messages from its neighbouring nodes, check its destination, transmit the messages to the next node, and then goes back to sleep. That is why relay node spends much of its energy to wake up and sleep. It can be seen in Figure 5 that the relay nodes run out of energy at 97th round of simulation compared to the simulation of source node (Figure 4) that stops at 222nd round. On average, the relay node used 58.69 times more energy than the source node.

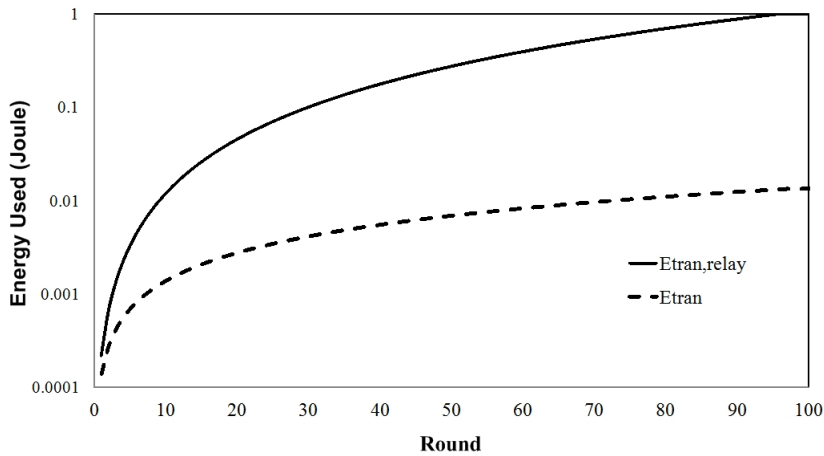


Figure 9. Energy consumption of a relay node. The energy use shown is in the logarithmic scale

Figure 10 shows the energy consumption of a base station node, the node that receives all messages transmitted by source nodes in the network. Again, the difference between $E_{tran,BS}$ and E_{tran} is significant. To see which type of sensor node (source, base-station, relay node) consumes more energy, the energy profile of each type is plotted in Figure 11.

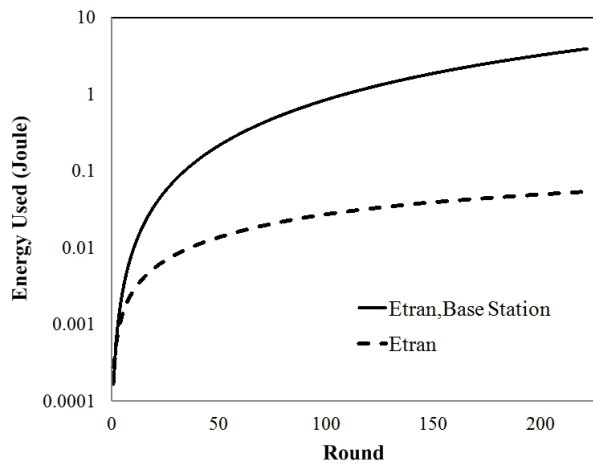


Figure 10. Energy consumption of a base station node. Energy use shown is in the logarithmic scale

As shown in Figure 11, energy consumption of the relay node is the highest compared to the other nodes, followed by the base station node and source node. From the second and third term of Equation (10) above, we can see that the relay nodes spent most of its energy to receive messages and wake up and sleep, respectively. Depending on how many messages it needs to relay to the other nodes, the relay node consumes more energy compared to other types of node.

Based on Figure 11, energy consumption of the base station node is significantly higher than the source node. Base station node has a duty to receive all messages from all the other nodes, so it spends most of its energy in receiving messages. According to Table 1 above, I_{onr} value or current in the receive mode is bigger than I_{ont} or current in the transmit mode, indicating that it needs more energy to receive messages than to transmit them. Furthermore, current is needed to wake up the radio transceiver to receive state $I_{tr,receive}$ is higher than the current needed to wake up to transmit state $I_{tr,transmit}$. This means it needs more energy to wake up into receive state than that to $t_{transmit}$ state. The same thing happens to $I_{tr,down,receive}$ and $I_{tr,down,transmit}$, which need more energy to sleep from the receive state than that from transmit state. Compounding all the effects into the total $E_{trans,BS}$ we can see that energy consumption of base station nodes is higher than source node.

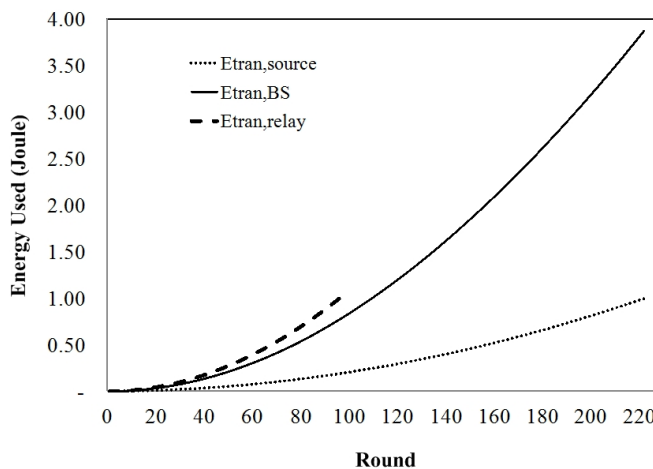


Figure 11. Energy consumption of various node types (source, base station, relay). Energy Use shown is in logarithmic scale

CONCLUSION

Simulation of the WSN network using multi-hop routing protocol was done in this study. For the random topology network, sensor nodes placement is very important to maximise the lifetime of the network. Relay nodes consume more energy than ordinary nodes, so sensor placement that efficiently reduces the number of relay nodes in the network is needed.

It was found that the grid topology has better performance, especially in small network size. However, when the number of nodes in the network increases, the performance of Random topology network exceeds the grid's performance.

The lifetime of the WSN network does not depend on the size of the network and topology, but rather determined by the available energy in each sensor node. We also have successfully improved the energy consumption model proposed in the previous research to account for more parameters of radio transceiver used in a WSN node. The energy needed to wake up and sleep the radio transceiver plays a significant part in the energy consumption of the sensor node.

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