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Energy and Power Analysis of RPL under Topology Variations

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Abstract: IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) is a technology that finds use in low power nodes for data transmission. Low power and lossy network (LLN) consist of resource constrained battery operated nodes whose energy depletion has a substantial effect on the longevity of the network. The aim of the proposed research is to analyze the energy consumption of nodes in the network. Energy consumption in four different states namely Transmission (TX), Reception (RX), ON and Idle have been analyzed, to formulate an Objective Function that can mitigate energy depletion problem in the network. The analysis has been carried out for two topologies, namely, linear and random and their performances are compared. The work has been simulated using a Cooja Simulator. The inference from the results is that linear topology spends more energy compared to random topology. The reason is that linear topology consists of relay nodes which increase energy consumption in the network.

Keywords: 6LoWPAN, RPL, Objective Function, Transmission, Reception, Idle, ON and energy consumption.

I. Introduction

6LoWPAN is a technology that facilitates D to D communication with the help of the Internet. These devices are compact with constrained processing capability. The network created with these devices is known as LLNs. The devices play two roles, namely, the sensing and routing. RPL is a distance vector routing protocol designed and developed by IETF working group to assist IPv6 communication in LLNs.

The protocol supports MP2P traffic. RPL is defined in Request for Comments RFC 6550 document of IETF in which the LLN is assumed as a graph consisting of edges and vertices. It constructs a DODAG at the root and utilizes OF for reducing the routing cost involved in the establishment of routing in the network.

Routing data packets is the fundamental mechanism in every LLN. Rapid depletion of energy takes place in the nodes in the network as they are battery operated. This may lead to unreliability in routing path. There is a possibility of occurrence of network partitioning when surplus numbers of nodes cease to exist. Therefore, energy consumption must be taken as a critical factor in enhancing the lifetime of nodes in the network.

Findings from literature show the increase in network lifetime can be achieved by developing energy aware routing protocol. A new "OF" that takes into account the residual energy of nodes involved in routing needs development. Hence the objective of the proposed work is to analyze the energy consumption of nodes in the network thereby helping formulation of "OF" which can enhance network lifetime. The analysis has been carried out for two topologies, namely, linear and random. Then their performances are compared. Abbreviations and expansions related to the work are tabulated in Table I. Table II shows the symbols and their meanings utilized in the proposed research.

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TABLE I
ABBREVIATIONS AND EXPANSIONS

ABBREVIA-TIONS	EXPANSIONS
6LoWPAN	IPv6 over Low Power Wireless Personal Area Networks
D to D	Device to Device
LLN	Low Power and Lossy Network
RPL	IPv6 Routing protocol for Low Power and Lossy Networks
IETF	Internet Engineering Task Force
MP2P	Multi-Point to Point
RFC	Request For Comments
DODAG	Destination Oriented Directed Acyclic Graph
OF	Objective Function
BRPL	Backpressure RPL
RER	Residual Energy Ratio
BDI	Battery Discharge Index
ETx	Expected Transmission Count
PDR	Packet Delivery Ratio
RSSI	Received Signal Strength Indicator
LQI	Link Quality Indicator
SNR	Signal to Noise Ratio
EAOF	Energy-Aware Objective Function
MRHOF	Minimum Rank Hysteresis Objective Function
HECRPL	Hybrid, Energy efficient and Cluster-parent based RPL
CPS	Cluster-Parent Set
ER-RPL	Energy-efficient Region based Routing Protocol
IP	Internet Protocol
DIS	Destination Information Solicitation
IRPL	Improved RPL
SLIP	Serial Line Interface Protocol
TX	Transmission
RX	Reception
BR	Border Router
mJ	milli-Joules

The rest of the paper is organized as follows: Section II elaborates the inference drawn from literatures related to the proposed work. Section III elucidates the proposed methodology. Results and inferences are deduced in Section IV. Finally, Section V concludes the paper with the directions for future research.

TABLE II
SYMBOLS AND MEANINGS

SYMBOLS	MEANINGS
E_o	Energy consumption in ON state
E_t	Energy consumption in TX state
E_r	Energy consumption in RX state
E_i	Energy consumption in Idle state
P_t	Power depletion in TX state
P_r	Power depletion in RX state
P_i	Power depletion in Idle state
P_o	Power depletion in ON state
I_t	Current consumption in TX state
I_r	Current consumption in RX state
I_i	Current consumption in Idle state
I_o	Current consumption in ON state
V	Operating Voltage
τ_t	Time spent for TX state
τ_r	Time spent for RX state
τ_i	Time spent for Idle state
τ_o	Time spent for ON state
E	Total Energy Consumption
P	Total Power Consumption
τ	Mote startup delay
t_s	Simulation time

II. LITERATURE SURVEY

In [1], the authors have addressed the issues of throughput, time-varying data traffic and mobility issues in RPL and developed BRPL, an extension of RPL that combines the RPL OF with backpressure routing. The developed BRPL utilizes two control algorithms, namely, QuickTheta ad QuickBeta to address the above issues. Results from simulation using Cooja simulator with cloud server and real test-bed experiments using FIT-IoT lab developed BRPL show improvements in throughput and support mobility and changes in data-traffic in the network. There is also a 60 % reduction in packet loss when compared with RPL.

In [2], the authors have developed an enhanced RPL routing protocol that combines two metrics, namely, RER and BDI of the nodes for the improvements of network lifetime. An objective function OF_{RBE} comprises RER, BDI and ETx has been developed to help improvement in network PDR. It is simulated using the Cooja simulator.

Performance analysis has been made in terms of network lifetime, PDR and energy consumption. The results show that the developed enhanced RPL protocol have improved network lifetime by reducing energy consumption. Further improvement in PDR has been achieved by the developed OF. The presented work can also be extended to analyze the impact of other link quality metrics, namely, RSSI, LQI and SNR in enhancing the network performance.

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In [3], Carlos Abreu et al have developed an EAOF for RPL to improve network lifetime for E-Health applications. The developed EAOF uses ETX and node residual energy as metrics to compute the best routing path. ETX is a metric used for avoiding the effect of Electro-magnetic Interference faced by Biomedical Wireless Sensor Network. Residual energy is used for the discovery of the energy aware routing path. A comparison of the developed work with MRHOF has been made in terms of ETX metric. The inference drawn is that the developed EAOF improves network lifetime by reducing energy consumption in the network.

In [4], the authors have developed a HECRPL to achieve reliability and energy efficiency in the network. The authors have integrated a top down approach for CPS selection to minimize the energy exhaustion in the network. Loss recovery scheme has been utilized for detection and retransmission of misplaced packets. Simulation using NS-3 simulator shows that the developed HECRPL improves lifetime, energy efficiency and reliability when compared with the standard RPL. As spatial reuse feature cannot be fully utilized in developed RPL, the future work plans to implement network coding scheme for the exploitation of the above feature and also to mitigate congestion in the network.

In [5], the authors have developed an ER- RPL for enhancement of energy efficiency and reliability. Energy efficiency has been achieved by involving only a subset of nodes for routing. Selection of these nodes has been done on the basis of the region feature of the network. This region based routing results in the reduction of routing overheads. Every region in the DODAG is segmented into four sub-regions. Sub-region of every node is determined by the developed (ER-RPL) distributed self regioning algorithm.

Comparison of the developed protocol with P2P-RPL and RPL is made using NS-3 simulator. Performance analysis is made in terms of PDR, control overhead, average hop count and average end-to-end delay. Inference drawn is ER-RPL achieves energy conservation, lesser hop count and lower control overhead when compared to other protocols. The end-to-end delay in developed ER-RPL increases as traffic flow increases, however it is lesser than traditional RPL. The future work focuses to extend the developed work to mobile networks.

In [6], the authors have addressed the issues related to data delivery rates and reliability. The authors have investigated the reasons for high packet loss rates and developed a new RPL that makes use of cross-layering design approach. Replacement policy and insertion policy have been employed for the management of RPL and IP neighbor tables. A variety of link monitoring techniques namely unicast based active probing, passive monitoring, unicast DIS messages have been employed to estimate efficient link. Simulation using Cooja simulator shows the development of RPL achieves enhancement in packet delivery rates and manages energy consumption in comparison with Contiki RPL. The future work aims to further improve packet delivery rates using network coding, opportunistic transmission and data compression techniques.

In [7], the authors have addressed the issues of energy consumption and load balancing of traditional RPL. They have developed a balanced RPL- IRPL which employs a clustering algorithm and topology control model to address the above issues. An objective function is formulated with a direction angle and residual energy of relay nodes. The relay nodes that forward packets are determined using this objective function. Results from Cooja simulator show IRPL is consuming energy of a smaller magnitude through angle routing mechanism in cluster head rotation.

The literatures survey made shows the achievement of improvement in network lifetime through involvement of different parameters, namely, RER, BDI and ETX of the nodes in the computation of the best routing path. Further, objective functions have been developed to reduce the number of nodes involved in routing. The survey has helped devising mechanisms to improve network lifetime by taking link metrics to compute the path.

The objective of proposed work is to consider energy consumption that is battery power of nodes as a critical attribute to improvise the lifespan of the network. The major contribution made by the proposed work is the analysis of the performance of the nodes in the network in terms of energy consumption under both linear and random deployment.

III. PROPOSED METHODOLOGY

The proposed energy depletion analysis in motes on the application of a RPL routing protocol for forwarding data in the network is presented in this section. Nodes are assumed to be driven by batteries. Fig.1 shows the work flow involved in the proposed research. The analysis has been performed in a simulated environment using a Cooja simulator. Sky motes [8] which have built-in temperature, humidity and light sensors have been utilized in this work. The motes have been configured as sensing nodes and border router (sink) node. The nodes placed closer to the sink spend more energy than the others, as it is mostly involved in routing.

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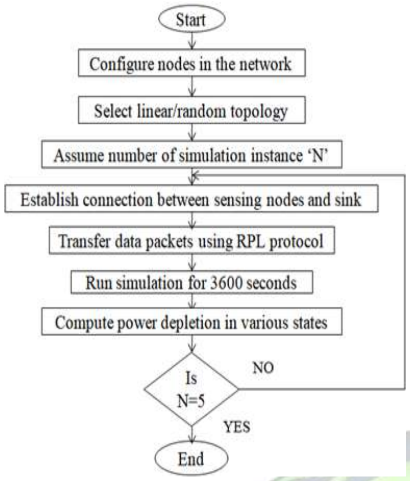

Fig. 1. Work Flow of Proposed Analysis

In a Cooja simulator [9], the connection between RPL network and local machine is established using the Tunslip package. Configuration of IPv6 address to a border router is made using SLIP. Assignment of IP address to nodes that are within the coverage of BR is done using SLIP. A node can be operated in various states, namely, TX, RX, ON and IDLE.

Let E_o be the energy consumed in ON state, E_t in TX state, E_r in RX state and E_i in IDLE state. The order of energy consumption in these states are represented as $E_r > E_t > E_o > E_i$. Hence, prolonging the network lifetime requires knowledge of the energy consumption of motes in these states to enable devising some control mechanism to avoid wastage of energy.

The power consumption in each mode is calculated using equations (1) to (4).

$$P_t = V * I_t \quad (1)$$

$$P_r = V * I_r \quad (2)$$

$$P_i = V * I_i \quad (3)$$

$$P_o = V * I_o \quad (4)$$

where V is the operating voltage and I_t, I_r, I_o, I_i be the current consumption in Transmission, Reception, ON and Idle states. Then the total power consumption in the network is computed using equation (5).

$$P = P_t + P_r + P_o + P_i \quad (5)$$

Let τ_t be the time spent for Transmission, τ_r for Reception, τ_o for ON and τ_i for Idle. Then the energy consumption [10] in each mode is computed using the equations (6) to (9).

$$E_t = P_t * \tau_t \quad (6)$$

$$E_r = P_r * \tau_r \quad (7)$$

$$E_i = P_i * \tau_i \quad (8)$$

$$E_o = P_o * \tau_o \quad (9)$$

With the knowledge of time spent in each mode, its corresponding energy consumption is calculated using equation (10).

$$E = E_t + E_r + E_o + E_i \quad (10)$$

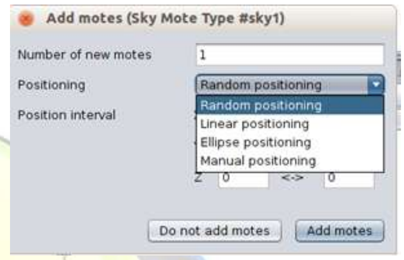

Fig. 2. Configuration of topology

Fig. 2 demonstrates the topology configuration in Cooja. The simulator supports four different topologies, namely, linear, elliptical, manual and random for node placement. The proposed analysis is restricted to linear and random topology.

Fig. 3 shows the Power Tracker plug-in present in Cooja which can be used for tracking the power usage in the network. This plug-in provides details relating to the power consumption involved in each simulation for various modes, namely, Radio ON, TX, RX and IDLE. Further, the average power used by all nodes including sink can also be obtained.

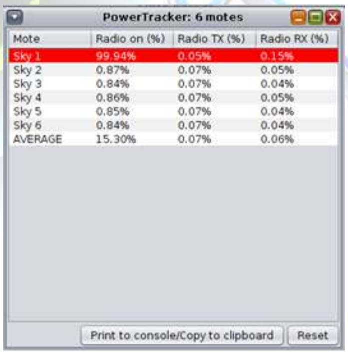

Fig. 3. Power Tracker plug-in

Radio messages [11] are displayed in table-like forms which indicate various activities performed by each node in every second. This data is analyzed for the determination of the time (seconds) taken by every node in different modes. Fig.4 shows the packet tracker plug-in of Cooja simulator.

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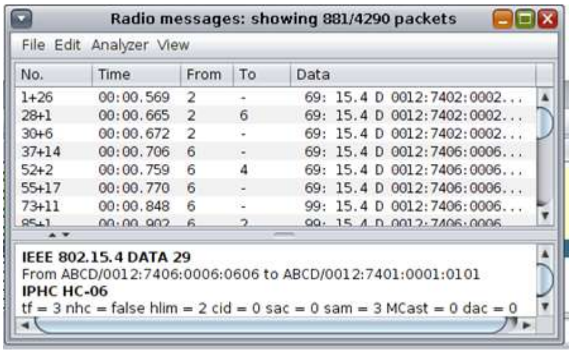

Fig. 4. Packet Tracker plug-in

The packet tracker plug-in present in Cooja provides complete information involved in data transfer in the network. They are nodes involved in packet forwarding, the IPv6 address of these nodes and time spent in data forwarding from source to sink.

IV. RESULTS AND DISCUSSION

In this research work, the performance of sky motes in 6LoWPAN is analyzed using Cooja Simulator. The total energy consumption in the motes is analysed for both linear and random topologies. To start with, analysis is made of the energy consumption in nodes for different modes namely TX, RX, ON and IDLE in both topologies. The simulation is repeated for 5 different instances, each of 3600 seconds. The simulation parameters [9] and their values are tabulated in Table III.

TABLE III

SIMULATION PARAMETERS

Parameters	Values
Area of Deployment	100*100 m^2
Radio Environment	Unit Disk Graph Medium: Distance Loss
Sink Node (BR)	1
Number of Client nodes (N)	5
Mote type	Sky Mote
TX Range	100 m
INT Range	100 m
TX Ratio	100
RX ratio	100
Simulation time (t_s)	3600s
Mote Start up delay (τ)	1000 ms
Scenarios considered	Linear and Random

The specifications of sky motes are tabulated in Table IV using the Sky Mote datasheet [8] and CC2420 datasheet [12].

TABLE IV

SKYMOTE SPECIFICATIONS

Specifications	Values
Typical output voltage (V)	1.8 V
Current consumption in TX mode (I_t)	17.4 mA
Current consumption in RX mode (I_r)	18.8 mA
Current consumption in IDLE model (I_i)	20 µA
Current consumption in ON mode (I_o)	365 µA

Figure 5 illustrates the energy consumed in the transmission mode when the nodes are in linear topology considering node 1 as BR and other nodes 2,3,4,5,6 as clients. From the results, it is inferred that every node is involved in transmission and consumes significant energy. Further, L1- L5 reveals the energy consumption involved in transmission by the nodes in the network for five different instances.

The nodes placed in linear topology are shown in figure 6. Nodes 2 and 4 are closer to border router whereas nodes 5 and 6 are placed in the range that is out of transmission of the border router. Therefore, the involvement of nodes 5 and 6 in transmission activity is found smaller and consuming energy in the range of 100 - 250 mJ. Nodes 2 and 4 consume a maximum energy of 1000 -1150 mJ.

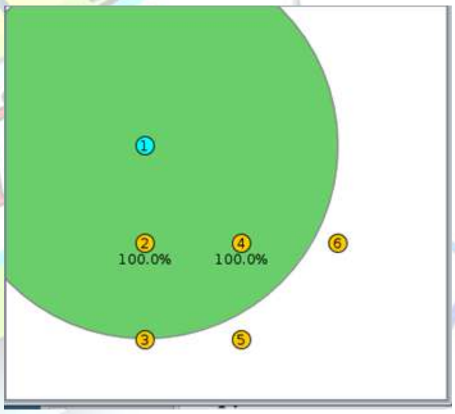

Fig. 6. Nodes placement in linear topology

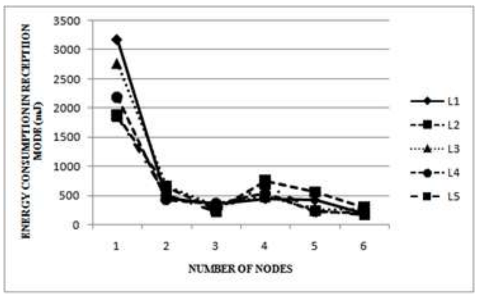

Fig. 7. Energy Consumption in reception mode

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Figure 7 depicts the energy utilized in the reception mode by the nodes in the network. The simulation results show clearly BR drawing a larger energy ranging from 1800-3200 mJ as it is designed to receive all the data packets from rest of the nodes in the network. Figure 8 illustrates the energy consumed by nodes in the network in idle state. The figure leads to the inference that all nodes in the network are present in an idle state. As node 6 is inactive during most of the time due to its location in the network, the energy consumed by it is large compared to others. As current consumption in the idle mode is 20 µA, the energy consumed is below 1 mJ which clearly indicates that negligible volume of the energy consumption in this mode is accomplished when compared to other modes.

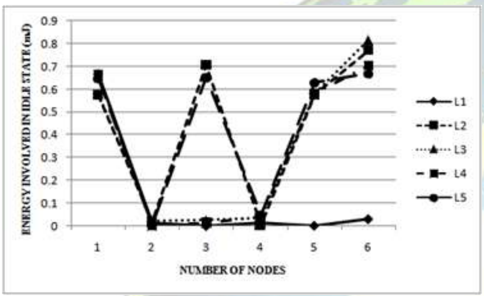

Fig. 8. Energy Consumption in Idle mode

Figure 9 shows the energy consumed by the network in the ON state. This state also consumes current in micro amperes (365 µA). But the energy consumed in this mode is far from negligible. Compared to the other nodes, the border router remains active most of the time, as it is ON for the transmission and reception of packets from the client nodes. Thus energy consumed by it in this state increases significantly.

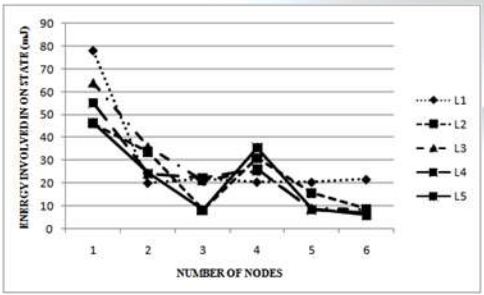

Fig. 9. Energy Consumption in ON mode

Figure 10 shows the total energy consumption in each node present in the network when deployed in linear topology. The results show that the consumption of maximum energy of 2300- 12500 mJ in five instances by the border router (node 1) in the network. This is due to the involvement of border router in activities such as TX RX, ON and Idle modes. Nodes 2 to 6 spends energy in the range of 450-6000 mJ in such instances which is almost equal in every instance.

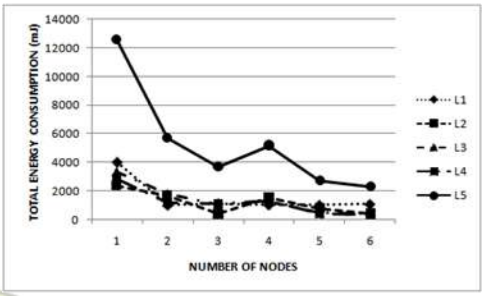

Fig. 10. Total Energy Consumption in the network

Figure 11 represents the average energy consumed in the transmission mode by the nodes in the network when placed under random and linear topology. The nodes placed in linear topology and random topologies are shown in figures 6 and 12 respectively. The inference from the linear topology is that node 2 and 4 spend more of its energy in transmission because these nodes act as relay nodes for 5 and 6. In random topology, all client nodes are placed within the transmission range of the border router. Hence, the energy consumed by the nodes in this topology is relatively equal as no energy is spent for relaying. Further, the consumption of energy by BR is higher than the other nodes as it is involved in a direct transmission.

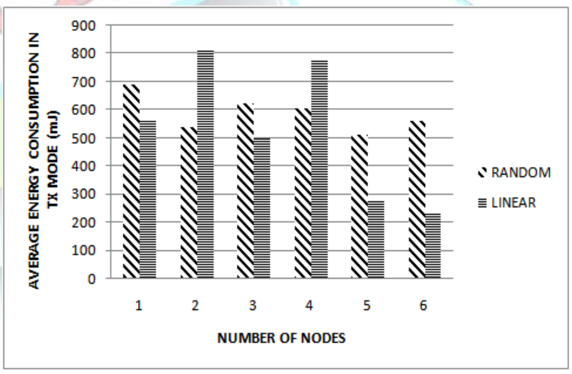

Fig. 11. Average Energy Consumption in TX mode

The average energy consumed by the nodes in the network during the reception mode is shown in Figure 13. Border router plays the role of a receiver receiving the packets sent from the client nodes. Therefore, there is increase in the energy consumption by it in both topologies.

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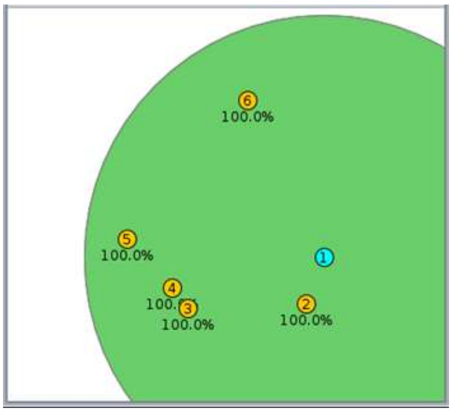

Fig. 12. Nodes placement in random topology

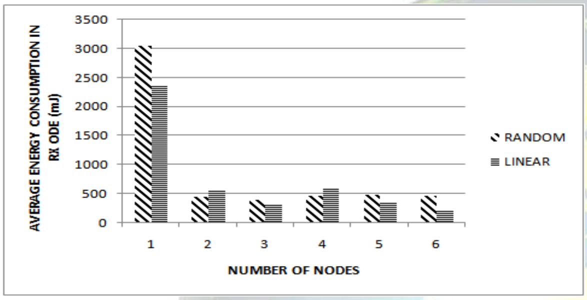

Fig. 13. Average Energy Consumption in RX mode

Client nodes consume energy in the range 0-544 mJ as their involvement is smaller in reception in both topologies. As stated earlier, nodes 2 and 4 in linear topology consume more energy than nodes 3, 5, 6 as they are the router for nodes 5 and 6. In random topology, negligible change in energy consumption is observed as all nodes are placed closer to border router.

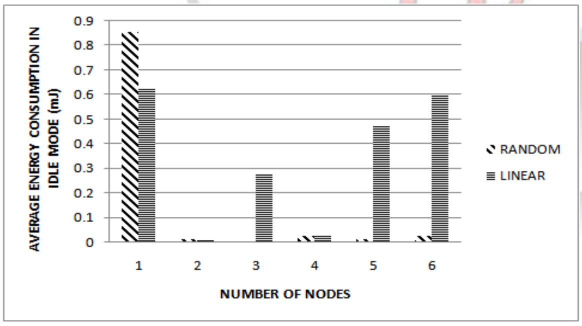

Fig. 14. Average Energy Consumption in Idle mode

The average energy consumption in idle mode by the nodes in the network under linear and random topologies is illustrated in figure 14. The energy consumption is done in the range of 0 to 1 mJ which clearly states that energy consumption in this mode is less. The inference from the figure is that all nodes are present in the idle state for some time.

Further, node 1 is available atleast 10 seconds in the idle mode while all the other nodes are available for a few seconds. As a result, node 1 consumes a maximum of 0.9 mJ approximately. Node 3, 5 and 6 in linear topology also consumes energy of a sizeable volume as they are not directly connected with border router and remains idle till there exists a path for data transfer.

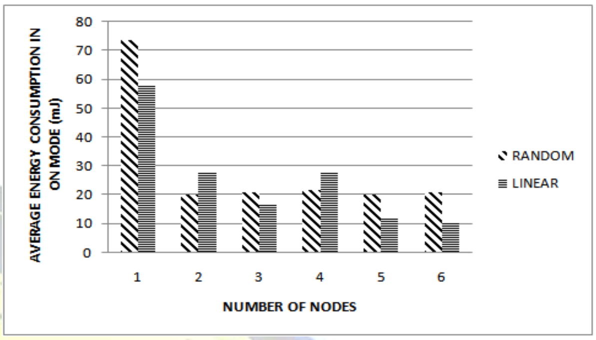

Fig. 15. Average Energy Consumption in ON mode

The average energy consumption in ON mode by both network topologies is shown in figure 15. Since current consumption in ON mode is in the order of micro amperes, energy consumption falls in the range of 0-100 mJ. Node 1 consumes about 75 mJ and 55 mJ in random and linear scenarios whereas other nodes in random consumes 20 mJ. In linear topology, nodes 2 and 4 are active most of the time and its energy usage in ON state increases automatically.

The average total energy consumption by the nodes placed in two different topologies is depicted in figure 16. The inference is that BR spends a maximum of 4-5 Joules when placed in the network. Client nodes spend 0.75-2.25 Joules for their involvement in different modes such as TX, RX, IDLE and ON for the duration of 3600 seconds (1 hour). Further, the energy depletion of the network can be estimated from the initial energy of the nodes in the network by taking away the energy spent in every consecutive hour.

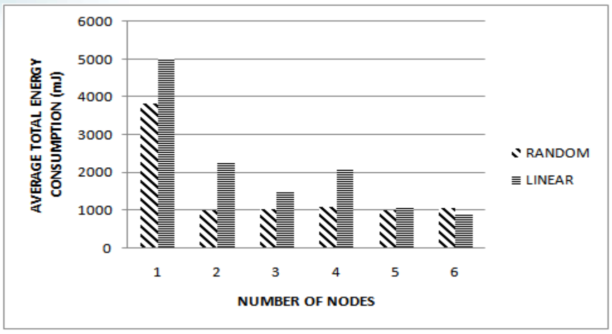

Fig. 16. Average Total Energy Consumption

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V. Conclusion and Future Work

In the proposed research work, analysis of the energy consumption of nodes in the network has been done for two topologies, namely, linear and random. The contribution of the work is the finding that the energy spent by the border router and client nodes in different states, namely, Transmission, Reception, IDLE and ON is determined for a 1 hour scenario. The result shows linear topology spending more energy than random topology as linear topology involves relay node. Further, the lifetime of the nodes can be calculated with the help of the proposed energy consumption analysis. The work can be extended to other topologies, namely, manual and elliptical for finding a better topology that consumes lesser energy. Detection of the deceased node in the network and avoiding it while routing is the future extension of the work. This is carried out by introducing duty cycling in the proposed energy consumption analysis.

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BIOGRAPHY

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