Energy Efficient Medium Access Control for Wireless Sensor Networks

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Summary
This paper aims to design an energy efficient Medium Access Control (MAC) for IEEE 802.15.4 based Wireless Sensor Networks (WSN). This is achieved by replacing the currently existing common-range maximum transmission power with the concept of dynamic and adaptive transmission power control. Various parameters like Link Quality, Received Signal Strength, MAC collisions, are considered for exercising the control on transmit power. These parameters are fuzzified and optimal transmission power levels are chosen based on Fuzzy decisions. The Sensor Network scenario is simulated with and without power control using Network Simulator NS2 and the comparative performance is analysed for a chosen network. It is seen that sensor network with power control saves energy without degrading the throughput of the network.

Keywords:
Wireless Sensor Networks (WSN), Medium Access Control (MAC) IEEE 802.15.4, dynamic power control, Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI), Energy Efficient Protocol.

1. Introduction

Wireless Sensor Network (WSN) [1] is a collection of small nodes, connected through a wireless channel, which performs the task of monitoring the environment and processing and communicating the gathered information. The main function of sensor networks is to sense the environment for physical data and to collect this data at a centralized location. This may involve a hierarchical structure, in which certain nodes summarize or fuse data as they forward it.

WSN falls under the category of Low Range Wireless Personal Area Network (LR-WPAN). The nodes consist of sensors, a radio transceiver, battery and an embedded processor. The main applications of sensor networks include industrial control, asset tracking and supply chain management, environmental sensing, health monitoring and traffic control. WSN is different from traditional ad hoc networks in cetain aspects such as being highly energy efficient, having low traffic rate, low mobility and predefined traffic patterns [1]. Energy conservation is a critical factor for the design of these networks. Energy conservation involves optimizing protocols at various layers of the protocol stack. Optimal placement of nodes in sensor field also contributes to energy conservation but typically the philosophy in WSN is to have a large number of cheap nodes which could fail and thus resilience in the distributed protocols is preferred over strategies such as an optimal placement of nodes. The major constraint in WSN is energy conservation since the sensor is required to operate under remote conditions without fresh supply of power to replenish itself.

1.1 WSN Architecture

A WSN device can be configured as one of the three types of nodes namely, a coordinator (PANCOORD), a router (RTR) or an end device (ED). The end device will sense the environmental conditions and will communicate the data to the co-ordinator. The router in addition to its normal routing operations can also act as an end device. The co-ordinator will collect the data from end devices and router and process them accordingly. A LR-WPAN normally consists of one coordinator, several routers and many end devices. All the nodes operate at a given transmit power irrespective of their location.

1.2 Energy Conservation in WSN

According to IEEE standard 802.15.4 MAC protocol [11], energy conservation is accomplished through idle modes and sleep modes in a sensor node. The node switches between active and sleep states based on the operations. During sleep states, all the blocks of the sensor mode are switched off, saving considerable power. The node wakes up at the time when it wants to transmit or when it expects information from the coordinator. The extent of sleep periods and active periods depends on the configuration of the network, namely, beacon-enabled mode and non-beacon-enabled mode.

Although this saves power considerably, there is a possibility of control over transmit power which can further bring down the energy spent on transmissions. Hence Several energy efficient algorithms and protocols

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have been proposed in the recent past, a few of which are detailed in the next paragraph. This paper proposes to provide control over transmit power dynamically and adaptively using Fuzzy decisions, for any given WSN environment. The reason for choosing Fuzzy type of control is two-fold: First, the channel parameters are highly dynamic and accurate calculations are either meaningless or unnecessary. Secondly, the complexity of the control algorithm is much simplified while using Fuzzy logic.

1.3 Related Work

In [2], A Power Aware Dynamic Source Routing (PADSR) protocol was proposed by the authors for enhancing the traditional DSR protocol with power awareness. The Location Aided Power Aware Routing (LAPAR) routing algorithm is used over DSR for controlling the transmit power. Here, the location information is assumed to be available in the individual nodes, and it is shared among all nodes during route discovery phase. The need for sharing location information and its periodic updates are the overhead in this protocol.
In [3], the authors have explored the possibility of finding the feasibility of PADSR protocol for scaled networks. The limitations of DSR protocol affects the performance as the packet overhead grows with network size.
In [4], the authors have proposed an enhancement technique at MAC level, wherein the transmissions to a congested node are minimized by passing the congestion information to all neighbours of the congested node. Each transmission by a node involves a considerable amount of energy spent by the node. The transmission power is approximately 100 times or more than the processing power [1]. So minimizing the number of transmissions will extend the lifetime greatly. Through the improvement suggested in [4], the wasteful transmissions leading to dropped packets are brought down. This saves the power in all the nodes along the path in which a congested node is encountered. However, the possibility of an already congested node informing its neighbours about its congestion status is an issue to be addressed.
Various power and energy efficient protocols have been proposed in [5 - 10]. The rest of the sections are organized as follows: Section 2 gives the concept of Dynamic Power Control. Section 3 details the Analysis of a WSN under controlled conditions. This is required to arrive at the control values. Section 4 gives the Dynamic Power Control algorithm developed based on the observations. Section 5 gives the comparative analysis of WSN performance with and without dynamic power control. Finally, Section 6 gives the conclusions and the current work under progress.

2. Dynamic Power Control

Dynamic Power Control concept is already introduced in Cellular Mobile Communication in "Power Management" [12] wherein the Base Station monitors the RSSI of the mobile and tells the mobile to decrease or increase its transmit power accordingly. However, this is not possible in an ad hoc network or a sensor work as there is no centralized control stations to do the job. The coordinator of a sensor network may be treated equivalent to a Base Station of a Cellular System but often the former is not equipped with immense processing capabilities as the latter, particularly in a scenario where the coordinator itself is connected through wireless channel to the base network. Dynamic power control has been proposed in several papers for Ad hoc networks based on IEEE 802.11 MAC [10].
This paper proposes a protocol to be implemented in devices that follow the IEEE 802.15.4 standard such that the transmit power varies with respect to RSSI, LQI and Collisions / Dropped Packets between a pair of communicating nodes. The throughput is then compared with the implementation without power control.
The distance between the mobile nodes has a direct relation to LQI and RSSI [5]. Using a look-up table, the factors RSSI, LQI and collisions are divided into three ranges and the transmit power is varied in five levels based on those values. Based on this table several decisions can be taken and hence the best or optimal transmit power is chosen using experiments which are briefed in the next section.

3. Analysis of WSN under controlled conditions

The required transmit power levels are obtained by observing the parameters under consideration for an ideal network scenario. The simulation environment is created with the parameters as given in Table 1.
The LQI, RSSI and Dropped packets are collected from the following network scenarios through simulation:
The LQI, RSSI and Dropped packets are collected from the following network scenarios through simulation:
Case (i) A WSN having only two nodes with 2 Ray Ground Reflection Propagation Model: The distance is varied gradually while a CBR data transfer (1024 bytes/pkt) is induced in the transmitting node. The variations in RSSI, LQI and collisions are observed in the receiving node and plotted using Network Simulator NS2 [14]. Fig.1 shows the Network Animation (NAM) screenshot of WSN with 2 nodes. Fig. 2 and Fig. 3 show the RSSI and LQI variations with respect to increasing distance of separation between the nodes. It is observed

that the RSSI variation corresponds to the typical large scale propagation model where the received power degrades exponentially with distance.

Table 1: Parameters used to create Simulation Environment

Sl. No.	Parameters	Values
	Fixed Parameters	
1	Frequency of operation	914 MHz
2	Receiver Threshold	-82 dBm
3	Carrier Sense Threshold	-92 dBm
4	MAC Protocol	IEEE 802.15.4
5	Network Routing Protocol	AODV
6	Traffic	CBR 512 bytes/pkt
7	Simulation Time	200 seconds
	Variable Parameters	
1	No. of nodes	2 / 4 / 6 / 25 (Four scenarios)
2	Mobility	Induced Mobility in selected nodes
3	Transmit Power	Varied from 0.2 W to 0.2818W
4	Propagation Model	Two Ray Ground Reflection / Log Normal Shadowing

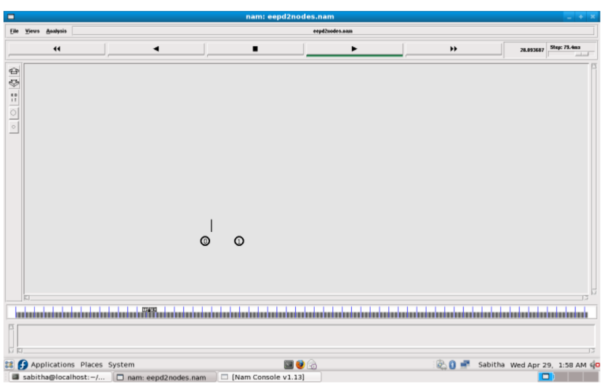

Fig. 1 NAM screenshot of WSN with 2 nodes

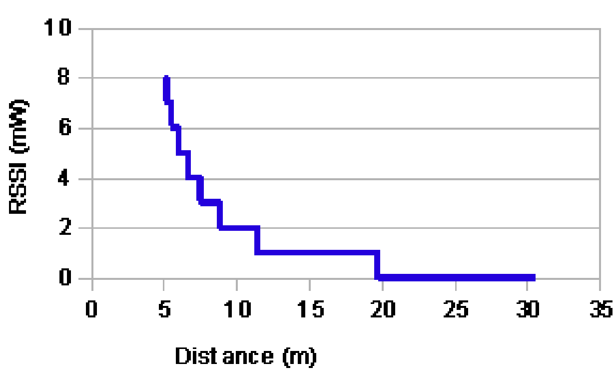

Fig. 2 RSSI vs distance for WSN with 2 nodes using Two Ray Ground Reflection Propagation Model

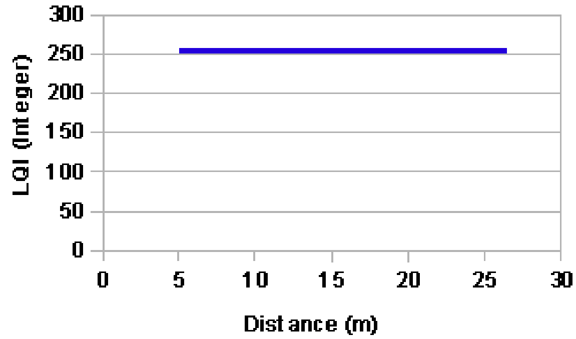

Fig. 3 LQI vs distance for WSN with 2 nodes using Two Ray Ground Reflection Model

Case (ii) A WSN having only two nodes which includes Log Normal Shadowing: It is observed that RSSI fluctuations are more here than case (i). This is because of the multipath fading characteristics due to Shadowing model. Fig. 4 shows the NAM screenshot of the WSN scenario. Fig. 5 and Fig. 6 show the RSSI and LQI variations with respect to increasing distance of separation between the nodes. It is observed that the RSSI fluctuations are rapid because of the randomness induced in the channel due to Log Normal Shadowing.

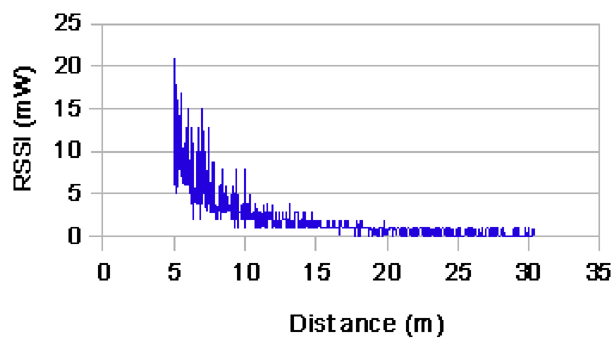

Fig. 4 RSSI vs distance for WSN with 2 nodes using Log Normal Shadowing Model

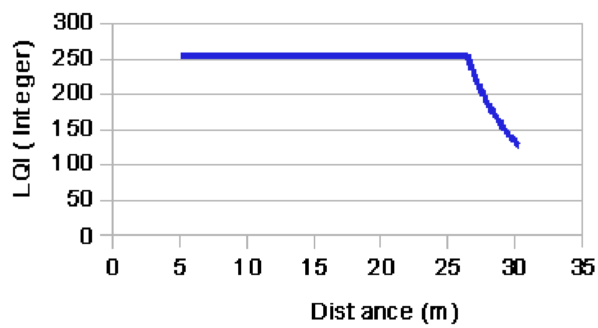

Fig.5 LQI Vs distance for WSN with 2 nodes using Log Normal Shadowing model

Case (iii) A WSN having 4 nodes using Two Ray Ground Reflection Model. Two nodes are of interest and the remaining two nodes induce traffic and create interference: It is observed that RSSI fluctuations are more here than case (i). This is because of the multipath fading characteristics and also due to the interference from other traffic. Fig. 6 shows the NAM screenshot of 4 nodes, in which nodes 0 and 1 are of interest and nodes 2 and 3 induce interference. Fig. 7 and Fig. 8 show the RSSI and LQI variations with respect to increasing distance of separation between the nodes for Two Ray Ground Reflection model. The LQI degrades whenever there is a new traffic induced. However the LQI recovers after a finite period.

Fig. 2 and Fig. 3 show the RSSI and LQI variations with respect to increasing distance of separation between the nodes. It is observed that the RSSI variation corresponds to the typical large scale propagation model where the received power degrades exponentially with distance.

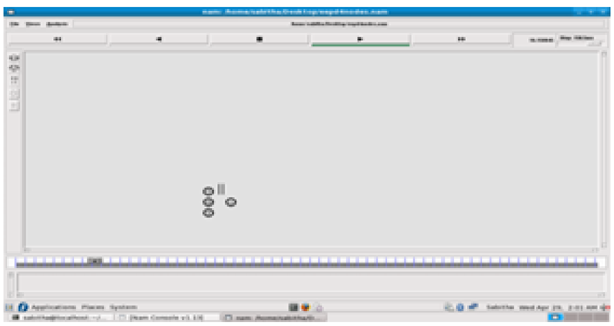

Fig. 6 NAM scheenshot of WSN with 4 nodes

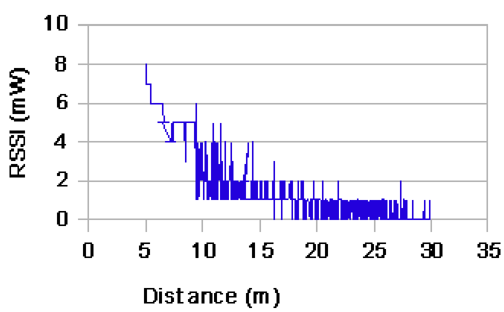

Fig. 7 RSSI vs distance for WSN with 4 nodes using Two Ray Ground Reflection model

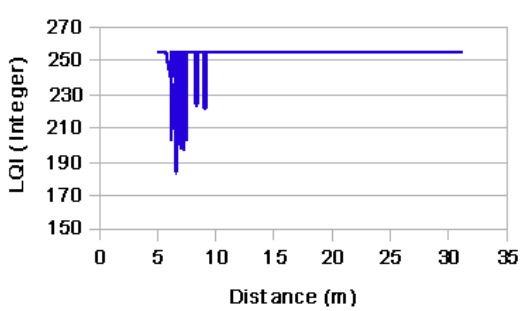

Fig. 8 LQI vs Distance for WSN with 4 nodes using Two Ray Ground Reflection model

Case (iv) A WSN having 4 nodes using Log Normal Shadowing Model. Two nodes are of interest and the remaining two nodes induce traffic and create interference: It is observed that RSSI range is more than case (iii). This is because of the multipath fading characteristics due to Shadowing model which has positive effects due to the shadowing effects. However the RSSI fluctuations are much more that case (ii).Fig. 6 shows the NAM screenshot of 4 nodes, in which nodes 0 and 1 are of interest and nodes 2 and 3 induce interference. Fig. 7 and Fig. 8 show the RSSI and LQI Vs distance of separation between the nodes for Two Ray Ground Reflection model.

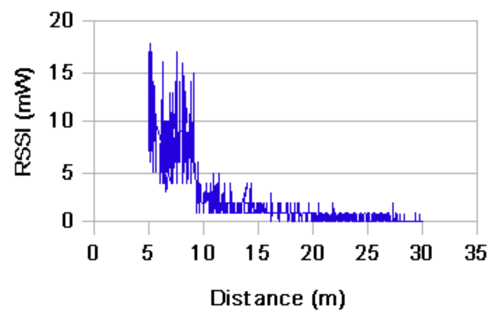

Fig. 9 RSSI vs distance for WSN with 4 nodes using Log Normal Shadowing model

The observations are taken for two more scenarios: WSN with 6 nodes and a typical WSN with 25 nodes with random node-placement. Every time, a pair of nodes are observed for RSSI, LQI, collisions and throughput. For avoiding monotony the graphs are not shown here. The NAM sceenshots alone are shown in Fig. 10 and Fig. 11

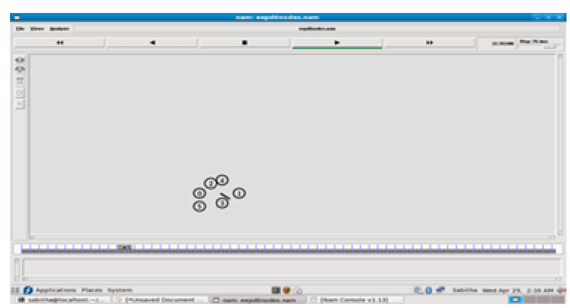

Fig. 10 NAM screenshot of WSN with 6 nodes

The basic analysis of IEEE 802.15.4 LR-WPAN based on the above observations reveals the following:

i) The Optimal placing of sensor nodes would be within 10m of the coordinator (or router).
ii) The RSSI varies between 2 mW and 8 mW for the 10m range in WSN using Two Ray Ground Reflection Model

iii) The RSSI varies between 2 mW and 15 mW for the 10m range in WSN using Log Normal Shadowing Model.
iv) The LQI variations are mainly due to the amount of traffic cumulatively induced by the nodes in the network at any point of time.
v) For two nodes the LQI value does not show any variation and is a constant at the maximum possible value of 255. This is because of no other traffic in existence.
vi) When more traffic is introduced in a network, the LQI degrades drastically at the time of inducing traffic but slowly recovers if no more new traffic is introduced. The range of LQI variation was found to be 150-255 for the scenarios chosen in our study.
vii) The dropped packets were found to be nil in the case of two nodes, and it increases as the network grows since the traffic grows with network size.

The above observations are used to formulate a look-up-table for controlling the Transmit Power of a node.

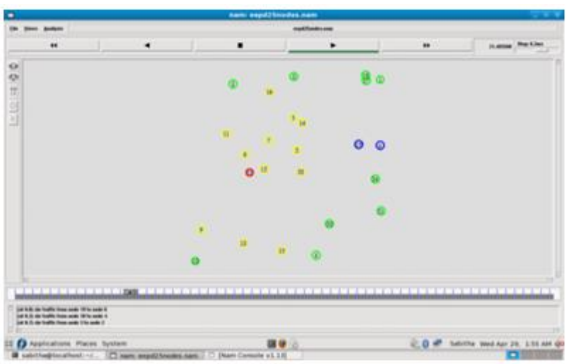
Fig. 11 NAM screenshot of WSN with 25 nodes

4. Dynamic Power Control Algorithm

The Dynamic Power Control algorithm is done at MAC level in which the power control can be done for the individual links separately. Primarily the two variables RSSI and LQI are considered for deciding the Transmit Power Pt. However the frame status will be used to fine tune Pt.
It is a fact that Dynamic Power Control can increase the Network capacity and reduce interferences. However, an inherent problem in Dynamic Power Control is the confusion that may arise due to increased hidden terminal problem [11]. To avoid this problem the proposed algorithm uses power control only on the DATA and ACK packets and not for the control packets.

The algorithmic steps are as follows:

Step 1: Find RSSI from the physical layer. Store it in 'RSSI' variable.

Step 2: Packetise and send it to MAC layer

Step 3: In the MAC layer , find LQI, Source MAC ddress and the status of the frame (normal, corrupted or collided). Store them in the variables LQI, MACSRC and ERR respectively.

Step 4: Calculate the average values of RSSI and LQI over a time period, i.e., 5 seconds and store it in variables ARSSI and ALQI respectively. Also store the total no. of error frames in TOTERR.

Step 5: Check if the packet type is DATA or ACK.

Step 6: Based on the accumulated values of TOTRSSI and TOTLQI, calculate Average RSSI and Average LQI.

Decide the transmit power using the following conditions:

Case 1: if ((RSSI==HI)&&(LQI==HI or MED))
Pt =LOW
Case2: if ((RSSI==HI)&&(LQI== LOW))
Pt =LOWMED
Case3: if((RSSI==MED&&(LQI==HI or MED))
Pt = MEDIUM.
Case4: if((RSSI==MED&&(LQI==LOW))
Pt = HIMED
Case5: if((RSSI==LOW)&&(LQI==LOW or MED))
Pt =HI
Case6: if((RSSI==LOW)&&(LQI==HI))
Pt =HIMED

Step 7: In case of Frame Errors >2, increase the Power level one step higher

Step 8 : Repeat the above steps for every 5 seconds

The following are the ranges selected for the various Fuzzy Type variables:

RSSI:	HI	> 10mW
	MED	[5 – 10 mW]
	LOW	< 5 mW
LQI:	HI	>200
	MED	[100 – 200]
	LOW	<100
Pt:	HI	0.2818W
	HIMED	0.26W

MED	0.24W
LOMED	0.22W
LOW	0.20W

5. Performance Analysis

The power control algorithm is implemented over the various network scenarios shown in Section III using Network Simulator NS2. The transmit power variations with respect to time and with respect to distance are shown below. Fig. 12 shows the transmit power vs distance for 2 nodes under various environments. The blue line shows the Transmit power without power control which is 0.2818W. The red line shows the Transmit power with power control. It varies between 0.22 to 0.2818mW. Fig. 13 shows the transmit power vs time for 4 nodes with and without power control for Shadowing model. The energy utilized is calculated based on the following equation:

Energy consumed = Σ (Pt*d)

where Pt = Transmit Power

d = Transmit time

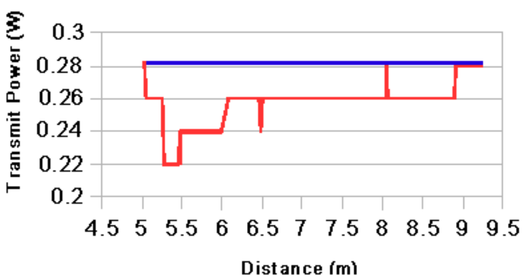

Fig. 12 Transmit Power vs Distance for WSN with 2 nodes with and without power control.

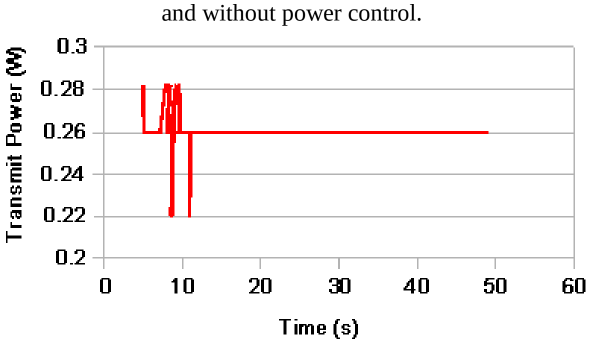

Fig. 13 Transmit Power vs Time for WSN with 4 nodes with and without power control

Table 2 summarizes the energy consumed by the WSN for various scenarios with and without Power Control. The throughput remains the same for both the cases with and without power control. This is because of the appropriate selection of transmit power (Pt) for the various combinations of RSSI and LQI and also due to the boost in Pt given while encountering error frames. Fig. 15 and Fig. 16 show the throughput for the WSN with 4 nodes and using Two Ray Ground Reflection Model plotted using Xgraph in Network Simulator NS2 [14].

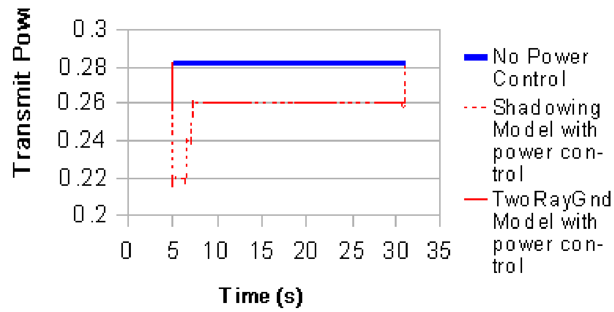

Fig. 14. Transmit Power vs Time for WSN with 6 nodes after implementing Dynamic Power Control

Table 2: Energy Consumption for WSN with and without Power Control

No. Of nodes in WSN	***Propagation Model***	***Energy (mJ) without Power Control***	***Energy (mJ) with Power Control***	***% Savings in energy***
2	Two Ray Ground Reflection	36.89	32.036	13.16
2	Shadowing	36.89	32.012	13.22
4	Two Ray Ground Reflection	35.23	31.23	11.35
4	Shadowing	36.92	32.82	11.11
6	Two Ray Ground Reflection	37.23	33.394	10.30
6	Shadowing	37.49	33.32	11.12
25	Two Ray Ground Reflection	43.23	38.62	10.66
25	Shadowing	42.92	38.23	10.93

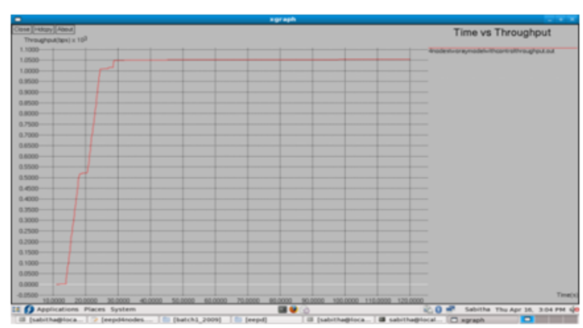

Fig. 15 Throughput of WSN with 4 nodes without power control

The throughput as seen from Fig. 15 and Fig. 16 are exactly the same. This shows that the dynamic power control does not degrade the performance of the network in terms of throughput.

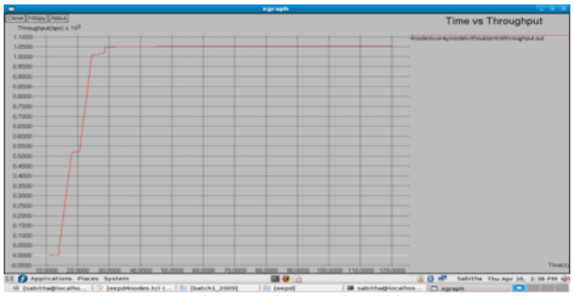

Fig. 16 Throughput of WSN with 4 nodes with power control

6. Conclusions and Work under Progress

Energy efficient protocol design is the need of the hour because of increasing need for independent sensor modules that could operate without utilizing much power so that the lifetime is extended. Through this project we enhance the performance of a WSN by employing dynamic power control at link level so that transmit power is controlled based on the received RSSI and LQI levels. While controlling the transmit power, rapid fluctuations (and thereby circuit instability) are avoided since the values are updated only once in 5 seconds. Also the power levels are chosen in such a way that they will not result in sudden drop in signal levels. The results are highly encouraging which motivates us to optimize the control further. This work is currently undertaken by the authors.

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