Investigations on Energy Efficiency for WSN Routing Protocols for Realistic Radio Models

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Abstract

In this paper, we have extended the Prowler simulator by integrating different realistic radio models into it and comparatively analyzed the effect of the channel behavior on the network layer specifically the WSN routing protocols. The simulation results indicate that the CF protocol consumes the highest energy amongst all the protocols in case of RMGMF while RTS protocol has the highest energy efficiency in case of NRM. Thus it has been concluded that the RTS protocol can be applied to achieve energy efficient routing in wireless sensor networks.

Keywords: *constraint-based routing, meta-strategies, real-time reinforcement learning, constrained flooding, real-time search, adaptive tree, wireless sensor networks*

1. Introduction

Sensor nodes are autonomous devices that are equipped with integrated sensing, processing and communication capabilities. A sensor network is the inter-networking of these nodes in an adhoc fashion. The nodes gather data via their sensors, process it locally or coordinate amongst their neighbors and forward the information to the user or a data sink. Being compact and wireless, they are highly energy constrained. Moreover, applications for sensor networks often require nodes to operate unattended for long periods of time on same batteries. However, it is infeasible to replace batteries of up to thousands of nodes. Thus, conserving energy so as to maximize lifetime is one of the key challenges in sensor networks. The basic operation of sensor networks is to gather the sensed data and transmit it to the base station for further processing or as result to a given query. The general scenario in these networks is that during data gathering the intermediate nodes can aggregate the data in order to avoid redundant transfers. The order in which the data or the aggregated data is transmitted from the source node to the base station is the problem of routing. Severe resource constraints in the form of limited computation, memory and power make the problem of routing interesting and challenging.

The routing layer is a subset of the network layer that lies above the MAC layer in the network protocol stack. It is used to build reliable and efficient communication links with other sensor nodes at the network layer including choosing communication paths whose links have the lowest associated cost (i.e. minimum hops, minimum energy level, and optimum medium quality), constructing and destructing paths with neighboring nodes, and maintaining routes. Y. Zhang, M. Fromherz and L. Kuhn, [2004] [1] proposed a framework of Message-initiated Constraint-Based Routing (MCBR), which consists of a QoS specification and a set of QoS-aware meta-strategies. The three learning-based meta-strategies stated use the reinforcement learning core.

A general message specification mechanism to explicitly encode the routing destinations, constraints and objectives in messages in order to apply general-purpose instead of objective or destination specific routing strategies has been reported by Y. Zhang and M. Fromherz, [2004] [2]. An MCBR protocol, together with both search-based and constrained-flooding meta-strategies, has also been implemented and demonstrated.

Y. Zhang and M. Fromherz, [2004] [3] studied search-based routing strategies for sensor networks. Theoretic analysis of search-based strategies has been done and performances of various strategies have been evaluated. However, the study does not investigate comparatively the explored strategy with other routing strategies.

An extension to the coordinated convergecast framework used for supporting various tasks in sensor network applications and the effectiveness of packet aggregation and duplication within this framework has been suggested by Ying Zhang and Qingfeng Huang, [2005] [4]. Using a layered routing architecture, other routing components such as aggregation for efficiency and duplication for high reliability have been integrated into the proposed framework. The drawback of the proposed framework is that though the coordinated convergecast improves reliability, its throughput is far from the maximum possible limit.

Y. Zhang and M. Fromherz, [2006] [5, 6] investigated a framework of constrained flooding protocols. The framework incorporates a reinforcement learning kernel, a differential delay mechanism, and a constrained and probabilistic retransmission policy. This type of protocol takes the advantages of robustness from flooding, but maintains energy efficiency by constraining retransmissions. Without the use of any control packets, such a protocol adapts to the specific routing requirements of the task and the dynamic changes of the network.

An adaptive spanning tree routing mechanism using real-time reinforcement learning strategies has been presented by Ying Zhang and Qingfeng Huang, [2006] [7, 8]. It was demonstrated that without additional control packets for tree maintenance, adaptive spanning trees can maintain the best connectivity to the base station, in spite of node failures or mobility of the base station. Moreover, two types of routing specifications, in addition to the shortest hop-counts, have been experimented i.e. energy-aware and congestion-aware to achieve load balancing and to control network congestion effectively in real time.

However, in the literature, it has been found that the performance of WSNs routing protocols has not been carried out in the presence of realistic fading models except for normal radio model (NRM). In this work, the authors have extended the Prowler simulator to include new radio models with Rician, Weibull, Lognormal fading and Gamma function. Subsequently, the effect of Constrained Flooding (CF) [5], Real-Time Search (RTS) [3] and Adaptive Tree (AT) [7] routing protocols on the energy consumption and energy efficiency of WSNs has been studied in case of radio model with SINR (RMSINR) radio model with Rayleigh fading (RMRYF), radio model with Rician fading (RMRCF), radio model with Weibull fading (RMWBF), radio model with Lognormal fading (RMLNF), radio model with Gamma function (RMGMF) and NRM.

Thus the main contribution of this paper is integration of the new radio models in Prowler and comparative analysis of energy use for CF, RTS and AT wireless sensor network protocols for the different radio models. The comparison has been done on the basis of various performance metrics such as energy consumption and energy efficiency. Here the performance evaluation is done by means of simulations using RMASE (Routing modeling Application Simulation Environment) [9], an application built on PROWLER (Probabilistic Wireless Network Simulator) [10].

The remainder of the paper is organized as follows. Section 2 describes the simulation model used. Section 3 analyzes the protocols via simulation and compares performances in case of NRM, RMSINR, RMRYF, RMRCF, RMWBF, RMLNF and RMGMF. Section 4 concludes the paper.

2. Simulation Model

In this section, we analyze the performance of the WSN protocols using Prowler and Rmase. A prowler is an event-driven tool that simulates the nondeterministic nature of the communication channel and the low-level communication protocol of the wireless sensor nodes [11]. It can incorporate arbitrary number of nodes on arbitrary and dynamic topology. It models all the important aspects of the communication channel and the application. The tool is implemented in MATLAB, thus it provides a fast and easy way to prototype applications and has nice visualization capabilities. Thus, we decided to use the prowler simulator in this work instead of other network simulators available such as TOSSIM, NS2 and OPNET.

2.1. Radio and MAC Models

The protocol study uses the MAC layer communication model and the radio propagation models: NRM, RMSINR & RMRYF provided by PROWLER as well as RMRCF, RMWBF, RMLNF and RMGMF developed by us.

The simple radio model in PROWLER attempts to simulate the probabilistic nature in wireless sensor communication observed by many. The propagation model determines the strength of a transmitted signal at a particular point of the space for all transmitters in the system. Based on this information the signal reception conditions for the receivers can be evaluated and collisions can be detected. The transmission model is given by [12]:

$$P_{rec,\,ideal}(d) \leftarrow P_{transmit}(1 / (1+d^{\gamma})),\ \text{where } 2 \leq \gamma \leq 4 \tag{1}$$

$$P_{rec}(i, j) \leftarrow P_{rec,\,ideal}(d_{i,j})\,(1 + \alpha(i, j))\,(1 + \beta(t)) \tag{2}$$

where $P_{transmit}$ is the signal strength at the transmitter and $P_{rec,\,ideal}(d)$ is the *ideal* received signal strength at distance d, α and β are random variables with normal distributions $N(0, \sigma_\alpha)$ and $N(0, \sigma_\beta)$, respectively. A network is asymmetric if $\sigma_\alpha > 0$ or $\sigma_\beta > 0$. Here α is static depending on locations i and j only, and β is dynamic which changes over time. A node j can receive a packet from node i if $P_{rec}(i, j) > \Delta$ where $\Delta > 0$ is the threshold. There is a collision if two transmissions overlap in time and both could be received successfully. Furthermore, an additional parameter p_{error} models the probability of a transmission error caused for any other reason. The default radio model in PROWLER has $\gamma = 2$, $\sigma_\alpha = 0.45$, $\sigma_\beta = 0.02$, $\Delta = 0.1$ and $p_{error} = 0.05$. Fig.1 (a) shows a snapshot of the radio reception curves in this model.

The transmission model for radio model with SINR in PROWLER is given by:

$$P_{rec}(i, j) \leftarrow P_{rec,\,ideal}(d_{i,j})\,(1 + \alpha(i, j)) \tag{3}$$

where all the variables have the same values and meaning as in case of normal radio model described above. Fig.1 (b) shows a snapshot of the radio reception curves in this model. The transmission model for radio model with Rayleigh fading in PROWLER is given by:

$$P_{rec}(i, j) \leftarrow P_{rec,\,ideal}(d_{i,j})\,(\mathrm{R}) \tag{4}$$

where R is a random variable with exponential distribution (mu=1). The coherence time is tau = 1 sec. Fig.1 (c) shows a snapshot of the radio reception curves in this model. The transmission model for radio model with Rician fading in PROWLER is given by:

$$P_{rec}(i, j) \longleftarrow \text{filter (chan, } P_{rec,\, ideal}(d_{i,j})\text{)} \qquad (5)$$

where chan = Ricianchan(ts, fd, k).Here ts = 1e-4 is the sampling time, fd = 100 is the doppler shift and k = 5 is the Rician factor. Fig.1 (d) shows a snapshot of the radio reception curves in this model. The transmission model for radio model with Weibull fading in PROWLER is given by:

$$P_{rec}(i, j) \leftarrow P_{rec,\, ideal}(d_{i,j})\text{ (R)} \qquad (6)$$

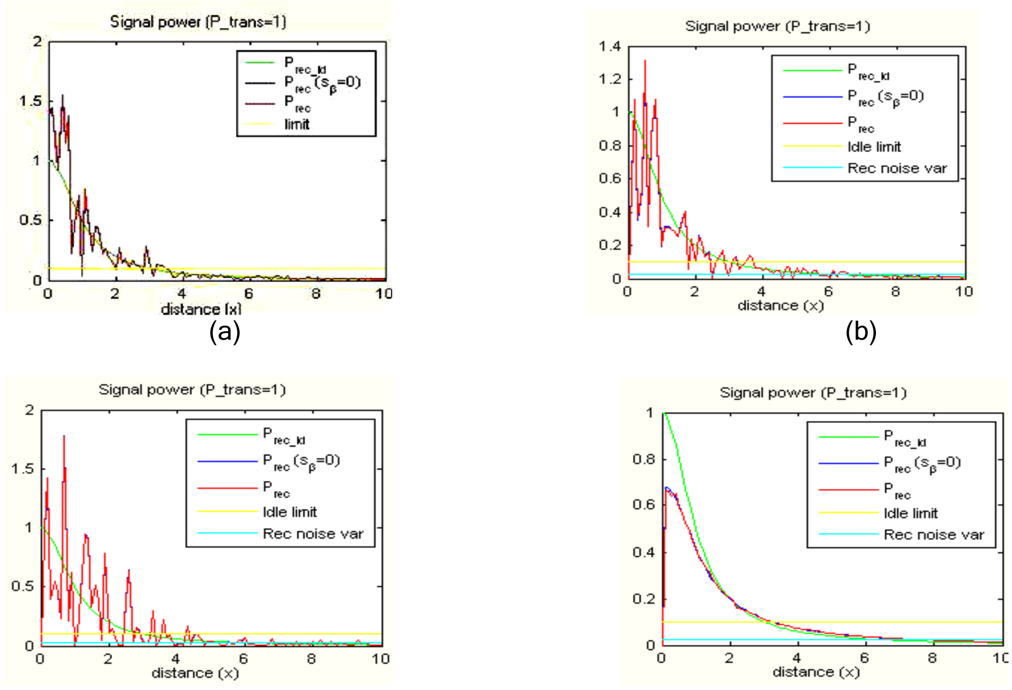
where R is a random variable with weibull distribution. Fig.1 (e) shows a snapshot of the radio reception curves in this model. The transmission model for radio model with Lognormal fading in PROWLER is given by:

$$P_{rec}(i, j) \leftarrow P_{rec,\, ideal}(d_{i,j})\text{ (R)} \qquad (7)$$

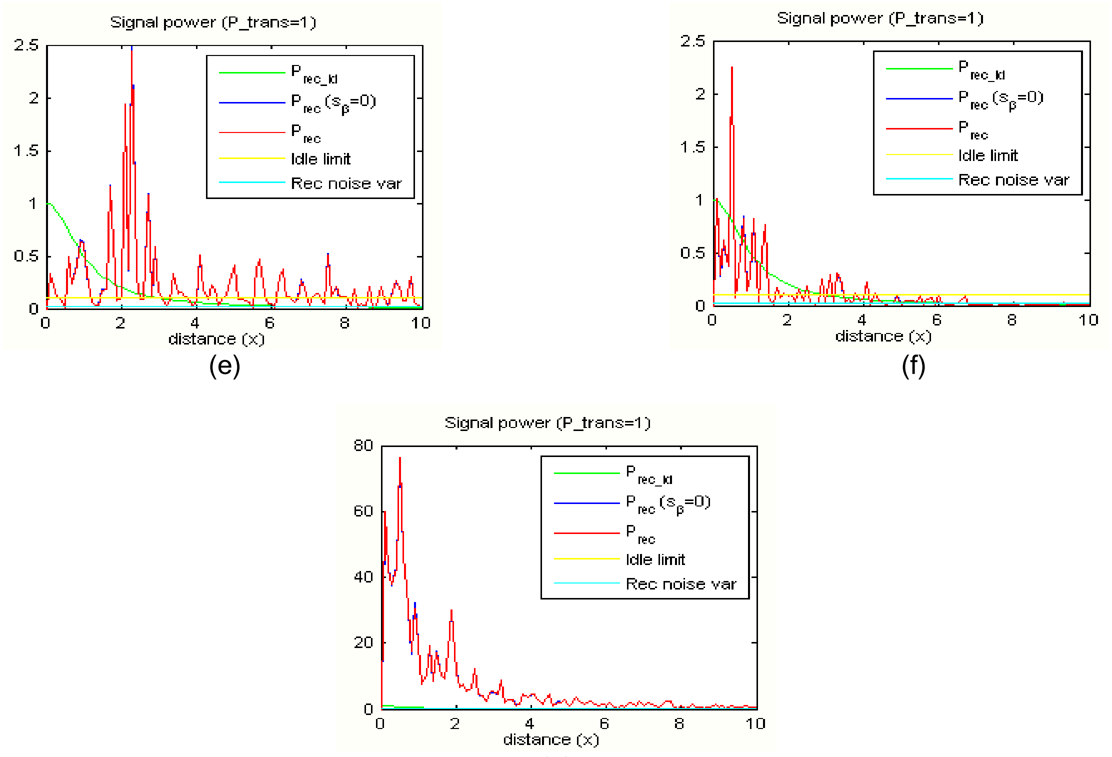
where R is a random variable with lognormal distribution (mu = log ((m^2) /sqrt(v+m^2)) and sigma = sqrt(log(v/(m^2)+1)); m=1; v=2). Fig.1 (f) shows a snapshot of the radio reception curves in this model. The transmission model for radio model with Gamma function in PROWLER is given by:

$$P_{rec}(i, j) \leftarrow P_{rec,\, ideal}(d_{i,j})\text{ (R)} \qquad (8)$$

where R is a random variable with gamma distribution. Fig.1 (g) shows a snapshot of the radio reception curves in this model.



(a) (b) (c) (d)



(e) (f)

(g)

Figure 1. Snapshot of radio reception curves for (a) NRM (b) RMSINR (c) RMRYF (d) RMRCF (e) RMWBF (f) RMLNF (g) RMGMF

The MAC layer communication is modeled by a simplified event channel that simulates the Berkeley motes' [13] CSMA MAC protocol. When the application emits the *Send Packet* command, after a random *Waiting Time* interval the MAC layer checks if the channel is idle.

If not, it continues the idle checking until the channel is found idle. The time between idle checks is a random interval characterized by *Backoff Time*. When the channel is idle the transmission begins, and after *Transmission Time* the application receives the *Packet Sent* event. After the reception of a packet on the receiver's side, the application receives a *Packet Received* or *Collided Packet Received* event, depending on the success of the transmission.

2.2. Routing Application Models

Our simulation tests were done in RMASE, an application built on PROWLER. RMASE provides network generation and performance evaluations for routing algorithms. RMASE supports a layered architecture, including at least the MAC layer, a routing layer, and the application layer, with the MAC layer at the bottom and the application layer at the top. It is the algorithm designer's choice to put individual functions at different layers so that common functions can be shared by different algorithms.

3. Results and Discussions

We use a real application to test the performance of the WSN routing protocols. The application, Pursuer Evader Game (PEG) [6], uses the sensor network to detect an evader and to inform the pursuer about its location. The communication problem in this task is to route packets sent out by one of the sensor nodes to the mobile pursuer. The source is changing from node to node, following the movement of the evader, and the destination is mobile. In our tests, the network is a 7x7 sensor grid with small random offsets. The maximum radio range is about 3*d*, where *d* is the standard distance between two neighbor nodes in the grid. Fig.2 shows an instance of the connectivity of such a network.

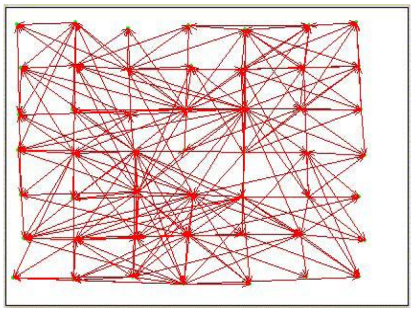


Figure 2. Instance of Radio Connectivity

The NRM, RMSINR, RMRYF, RMRCF, RMWBF, RMLNF and RMGMF are used in our experiments. The radio data rate is 40 kbps [14] and each packet has 960 bits. The application sends out one packet per second from the sources. The results are based on the average of 10 random runs.

3.1. Case 1: Constrained Flooding

Figure 3 shows that the energy consumption of the CF protocol is 100 initially stabilizing at 400 for NRM at simulation time of 13 sec. For RMSINR the energy consumption is 160 initially which then fluctuates to stabilize at 490 at simulation time of 13 sec. For RMRYF the energy consumption is 150 initially and stabilizes at 540 at simulation time of 14 sec. For RMRCF the energy consumption is 120 in the beginning and varies till simulation time of 13 sec to become constant at 420.

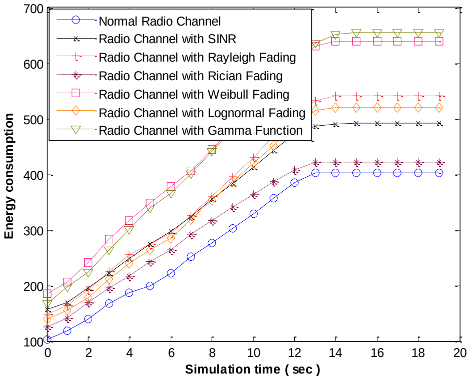


Figure 3. Energy consumption of different radio models for Constrained Flooding protocol

For RMWBF, RMLNF and RMGMF the energy consumption varies in the range of [190-640], [140-520] and [180-660] respectively. Thus, in case of CF it has been observed that the NRM and RMGMF show the lowest and the highest energy consumption respectively.

Figure 4 indicates that the energy efficiency of the CF protocol is 0.039 initially and decreases to 0.037 till simulation time of 13 sec and stabilizes for NRM. For RMSINR the energy efficiency is 0.028 initially which then decreases to 0.0315 at simulation time of 13 sec and stabilizes. For RMRYF the energy efficiency is 0.028 initially and stabilizes at 0.0285 at simulation time of 14 sec. In case of RMRCF, RMWBF, RMLNF and RMGMF the energy efficiency varies in the range of [0.035-0.0365], [0.024-0.0242], [0.028-0.026] and [0.024-0.0225] respectively. Thus, in case of CF it has been concluded that the RMGMF shows the lowest and the NRM indicates the highest energy efficiency amongst all the radio models.

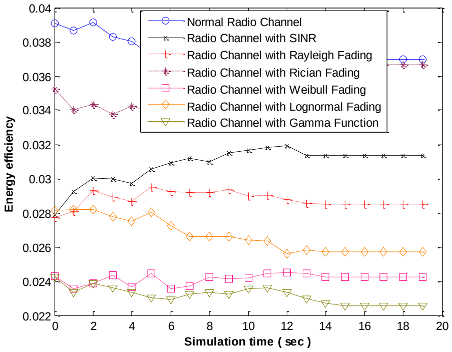


Figure 4. Energy efficiency of different radio models for Constrained Flooding protocol

3.2. Case 2: Real-Time Search

Figure 5 shows that the energy consumption of the RTS protocol is 10 initially stabilizing at 33 for NRM at simulation time of 13 sec. For RMSINR the energy consumption is 22 initially which then fluctuates to stabilize at 86 at simulation time of 13 sec. For RMRYF the energy consumption is 19 initially and stabilizes at 77 at simulation time of 12 sec. For RMRCF the energy consumption is 16 in the beginning and varies till simulation time of 13 sec to become constant at 123. For RMWBF, RMLNF and RMGMF the energy consumption varies in the range of [15-50], [29-140] and [10-32] respectively. Thus, in case of RTS it is evident that the energy consumption is lowest and highest for RMGMF and RMLNF respectively.

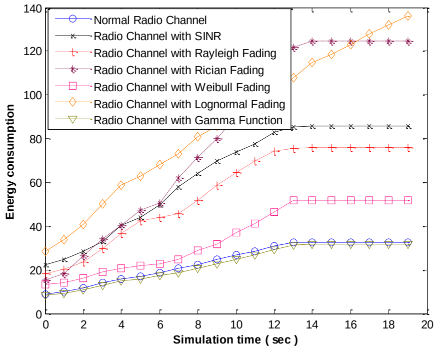


Figure 5. Energy consumption of different radio models for Real Time Search protocol

Figure 6 indicates that the energy efficiency of the RTS protocol is 0.50 initially and decreases to 0.47 till simulation time of 13 sec and stabilizes for NRM. For RMSINR the energy efficiency is 0.17 initially which then decreases to 0.15 at simulation time of 12 sec and stabilizes. For RMRYF the energy efficiency is 0.09 initially and stabilizes at 0.10 at simulation time of 13 sec. In case of RMRCF, RMWBF, RMLNF and RMGMF the energy efficiency varies in the range of [0.22-0.10], [0.19-0.20], [0.05-0.04] and [0.46-0.45] respectively. Thus, in case of RTS it has been observed that amongst the seven radio models the RMLNF shows lowest and the NRM indicate the highest energy efficiency.

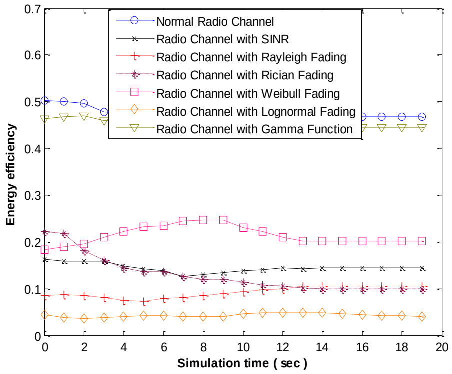


Figure 6. Energy efficiency of different radio models for Real Time Search protocol

3.3. Case 3: Adaptive Tree

Figure 7 shows that the energy consumption of the AT protocol is 20 initially stabilizing at 90 for NRM at simulation time of 14 sec. For RMSINR the energy consumption is 25 initially which then fluctuates to stabilize at 96 at simulation time of 13 sec. For RMRYF the energy consumption is 20 initially and stabilizes at 80 at simulation time of 14 sec. For RMRCF the energy consumption is 23 in the beginning and varies till simulation time of 14 sec to become constant at 122. For RMWBF and RMLNF the energy consumption varies in the range of [14-51] and [30-180] respectively. For RMGMF the energy consumption is 10 initially that fluctuates to stabilize at 31 finally. Thus, in case of AT it has been concluded that the RMGMF indicates the lowest and the RMLNF shows the highest energy consumption.

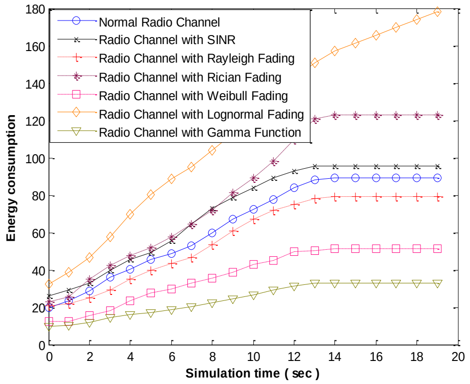


Figure 7. Energy consumption of different radio models for Adaptive Tree protocol

Figure 8 indicates that the energy efficiency of the AT protocol is 0.11 initially and increases to 0.13 till simulation time of 13 sec and stabilizes for NRM. For RMSINR the energy efficiency is 0.11 initially which then increases to 0.12 at simulation time of 13 sec and stabilizes. For RMRYF the energy efficiency is 0.08 initially and stabilizes at 0.10 at simulation time of 13 sec. In case of RMRCF, RMWBF, RMLNF and RMGMF the energy efficiency varies in the range of [0.17-0.10], [0.23-0.20], [0.06-0.04] and [0.42-0.44] respectively.

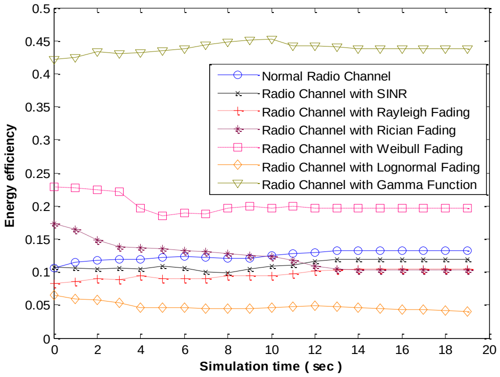


Figure 8. Energy efficiency of different radio models for Adaptive Tree protocol

Thus, in case of AT it is evident that the RMLNF shows the lowest and the RMGMF indicates the highest energy efficiency amongst all the radio models.

4. Conclusions

In this paper, the simulation results of the comparative investigation of the performance of routing protocols CF, RTS and AT for wireless sensor networks have been presented using advance wireless sensor simulator Prowler. The simulation results indicate that the AT protocol has the highest energy consumption in case of RMLNF while CF protocol has the highest energy consumption in case of RMGMF. Moreover, the RTS protocol has the highest energy consumption in case of RMLNF. The energy efficiency of AT protocol is better in case of RMGMF whereas for CF and RTS protocol it is better in case of NRM. The RTS protocol is more energy efficient than AT and CF protocols. Thus it has been concluded that the RTS protocol can be applied to achieve energy efficient routing in wireless sensor networks in case of NRM. Further, it has been inferred that the routing protocols behave differently in presence of different channel conditions.

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