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Comparative Investigations on Performance of Routing Protocols in Presence of Realistic Radio Models for WSNs

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Abstract

In this paper, we have compared and analyzed the Constrained Flooding, the Real-Time Search and the Adaptive Tree sensor network protocols on MICA platform using Prowler. The simulation results obtained show that the AT protocol has the highest throughput in case of RMGMF while CF protocol has the highest throughput in case of RMSINR. Further, the RTS protocol has the highest throughput in case of NRM. The lifetime of AT, CF and RTS protocols is better in case of RMGMF, NRM and RMGMF respectively.

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

1. Introduction

Wireless sensor networks (WSNs) contain hundreds or thousands of sensor nodes equipped with sensing, computing and communication abilities. Each node has the ability to sense elements of its environment, perform simple computations, and communicate among its peers or directly to an external base station (BS) [1]. Sensors seem to result in an explosive increase in data flows when networks become more ubiquitous. This increase in the number of sensors operating around us will result in an exposition. This will be the area of concern and also a number of new data mining tools would be required to be developed, which will help us in extraction of relevant information from the voluminous data. Thus, WSN technology is the measure for the future of Ubiquitous Computing. The motes preview a future pervaded by networks of wireless battery-powered sensors that monitor our environment, our machines, and even us. The wireless sensor networks are being extensively used in healthcare, environmental and ubiquitous computing fields.

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. This includes 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.

2. Related Work

A comprehensive review of the work reported in literature is briefly described in this section.

Y. Zhang, M. Fromherz and L. Kuhn, [2004] [2] 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] [3]. 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] [4] 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 studied the effectiveness of packet aggregation and duplication within this framework has been suggested by Ying Zhang and Qingfeng Huang, [2005] [5]. 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] [6, 7] 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. However, the experiments are done using the shortest-path routing objective only.

An adaptive spanning tree routing mechanism using real-time reinforcement learning strategies has been presented by Ying Zhang and Qingfeng Huang, [2006] [8, 9]. 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, the study does not specify the relationship between different parameters as well as the basis for selection of parameter values.

Agustin Barberis, Leonardo Barboni, and Maurizio Valle, [2007] [10, 11] experimentally evaluated a wireless sensor network simulator (i.e. Prowler) by comparing its behavior with the measurements obtained from experimental testbeds consisting of MICAz motes. In the experiments the simulator parameters have been tuned to match the testbeds features. Moreover, representative testbeds have been developed and appropriate metrics have been defined, in order to assess the comparison. The results indicate that the simulator under evaluation can effectively approximate, at MAC layer, the behavior of a wireless sensor network in terms of the numbers of sent and received packets and detected collisions.

In the literature, it has been found that the performance of WSNs routing protocols mentioned above has not been carried out in the presence of realistic fading models except for normal radio channel. In this work, new radio models with Rician, Weibull, Lognormal fading and Gamma function have been developed. Subsequently, the effect of Constrained Flooding (CF) [6], Real-Time Search (RTS) [4] and Adaptive Tree (AT) [8] routing protocols on the throughput and lifetime 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 performance analysis and comparisons of routing protocols CF, RTS and AT for wireless sensor networks in a simulated environment for MICA motes on MATLAB platform. The comparison has been done on the basis of various performance metrics throughput (data packets/sec), and lifetime (years). Here the performance evaluation is done by means of simulations using RMASE (Routing modeling Application Simulation Environment) [12], an application built on PROWLER (Probabilistic Wireless Network Simulator) [13]. Simulation results show that the adaptive tree protocol can be applied to achieve better energy consumption, efficiency and lifetime in real time. Further, use of MICAz motes decreases the energy consumption and increases the efficiency and lifetime of wireless sensor networks.

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

3. 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 [14]. 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.

3.1. 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 [15]:

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

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

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:

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

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:

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

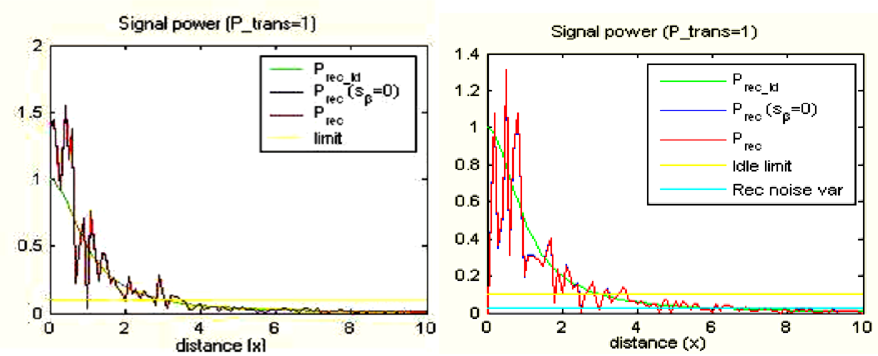
where R is a random variable with weibull distribution. Fig.1 (e) shows a snapshot of the radio reception curves in this model. The transmission model for radio model with Lognormal fading in PROWLER is given by:

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

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:

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

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



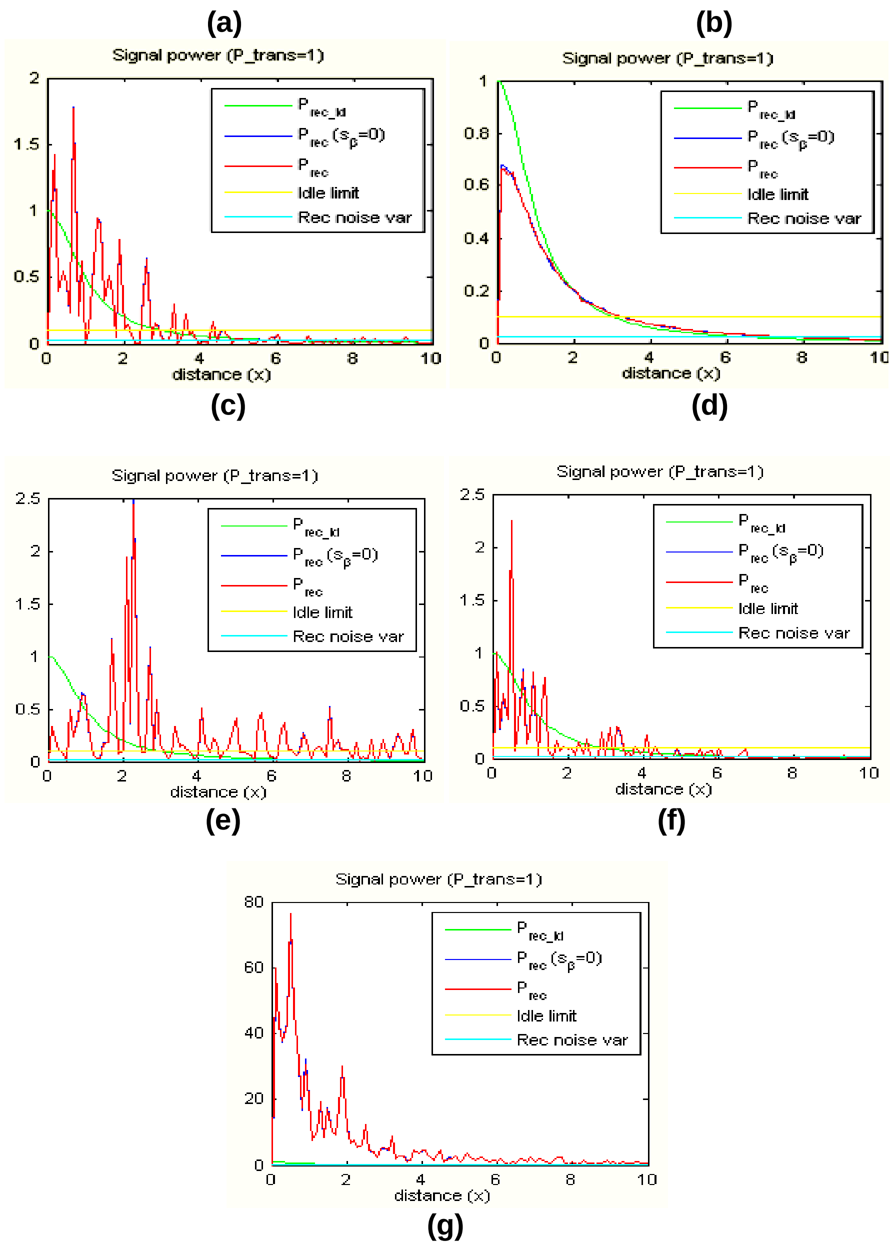


Figure 1. Snapshot of Radio Reception Curves for (a) NRM (b) RMSINR (c) RMRYF (d) RMRCF (e) RMWBF (f) RMLNF (g) RMGMF

The MAC layer communication is modeled by a simplified event channel that simulates the Berkeley motes' [16] 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.

3.2. 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.

4. Results and Discussions

We use a real application to test the performance of the WSN routing protocols. The application, Pursuer Evader Game (PEG) [7], 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.

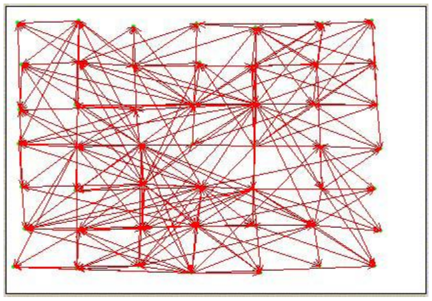


Figure 2. Instance of Radio Connectivity

The NRM, RMSINR, RMRYF, RMRCF, RMWBF, RMLNF and RMGMF are used in our experiments. The radio data rate is 40 kbps [17] 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.

4.1. Case 1: Constrained Flooding

Fig.3 shows that the throughput of the CF protocol is 0.84 data packets/sec initially stabilizing at 0.83 data packets/sec for NRM at simulation time of 13 sec. For RMSINR the throughput is 0.87 data packet/sec initially which then fluctuates to stabilize at 0.86 data packets/sec at simulation time of 12 sec. For RMRYF the throughput is 0.83 data packets/sec initially and stabilizes at 0.85 data packets/sec at simulation time of 13 sec. For RMRCF the throughput is 0.81 data packets/sec in the beginning and varies till simulation time of 13 sec to become constant at 0.85 data packets/sec.

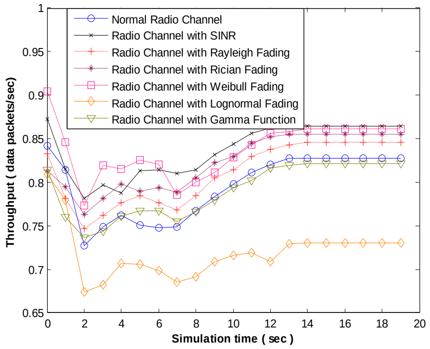


Figure 3. Throughput Comparison of Different Radio Models for Constrained Flood Protocol

For RMWBF, RMLNF and RMGMF the throughput varies in the range of [0.90-0.86], [0.81-0.73] and [0.81-0.82] data packets/sec respectively. Thus, in case of CF it has been observed that the RMLNF and RMSINR show the lowest and the highest throughput respectively.

Fig.4 indicates that the lifetime of the CF protocol is 1997 years initially and decreases to 1989 years till simulation time of 13 sec and stabilizes for NRM. For RMSINR the lifetime is 1996 years initially which then decreases to 1987 years at simulation time of 13 sec and stabilizes. For RMRYF the lifetime is 1996 years initially and stabilizes at 1986 years at simulation time of 14 sec. In case of RMRCF, RMWBF, RMLNF and RMGMF the lifetime varies in the range of [1996.5-1988], [1995-1984], [1996-1986.5] and [1996-1985.5] years respectively. Thus, in case of CF it has been concluded that the RMWBF shows the lowest (2 years) and the NRM indicates the highest (7 years) lifetime amongst all the radio models. The lifetime shows a decrease by 8.0, 9.0, 10.0, 8.5, 11.0, 9.5 and 10.5 years for NRM, RMSINR, RMRYF, RMRCF, RMWBF, RMLNF and RMGMF respectively in case of CF protocol.

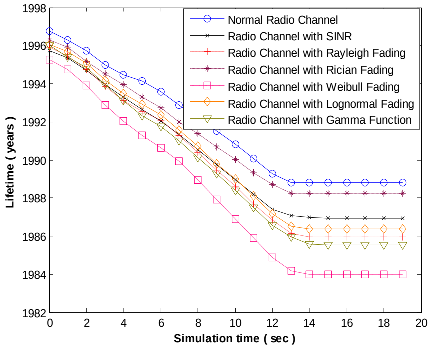


Figure 4. Lifetime Comparison of Different Radio Models for Constrained Flood Protocol

4.2. Case 2: Real-Time Search

Fig.5 shows that the throughput of the RTS protocol is 0.90 data packets/sec initially stabilizing at 0.85 data packets/sec for NRM at simulation time of 13 sec. For RMSINR the throughput is 0.75 data packet/sec initially which then fluctuates to stabilize at 0.68 data packets/sec at simulation time of 13 sec. For RMRYF the throughput is 0.31 data packets/sec initially and stabilizes at 0.46 data packets/sec at simulation time of 13 sec. For RMRCF the throughput is 0.73 data packets/sec in the beginning and varies till simulation time of 13 sec to become constant at 0.69 data packets/sec. For RMWBF, RMLNF and RMGMF the throughput varies in the range of [0.49-0.57], [0.26-0.29] and [0.80-0.77] data packets/sec respectively. Thus, in case of RTS it is evident that the throughput is lowest and highest for RMLNF and NRM respectively.

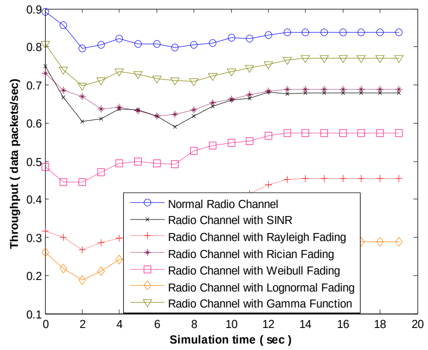


Figure 5. Throughput Comparison of Different Radio Models for Real Time Search Protocol

Fig.6 indicates that the lifetime of the RTS protocol is 1999 years initially and decreases to 1997 years till simulation time of 13 sec and stabilizes for NRM. For RMSINR the lifetime is 1998 years initially which then decreases to 1994 years at simulation time of 13 sec and stabilizes. For RMRYF the lifetime is 1999 years initially and stabilizes at 1995.5 years at simulation time of 13 sec. In case of RMRCF, RMWBF, RMLNF and RMGMF the lifetime varies in the range of [1999-1992.5], [1999-1996.5], [1998-1989] and [1999.5-1997] years respectively. Thus, in case of RTS it has been observed that amongst the seven radio models the RMLNF shows shortest (1 year) and the RMGMF as well as the NRM indicate the longest (9 years) lifetime. The lifetime indicates a decrease by 2.0, 4.0, 3.5, 6.5, 2.5, 9.0 and 2.5 years for NRM, RMSINR, RMRYF, RMRCF, RMWBF, RMLNF and RMGMF respectively in case of RTS protocol.

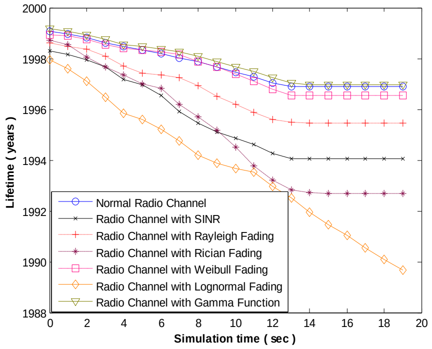


Figure 6. Lifetime Comparison of Different Radio Models for Real Time Search Protocol

4.3. Case 3: Adaptive Tree

Fig.7 shows that the throughput of the AT protocol is 0.47 data packets/sec initially stabilizing at 0.64 data packets/sec for NRM at simulation time of 14 sec. For RMSINR the throughput is 0.58 data packet/sec initially which then fluctuates to stabilize at 0.63 data packets/sec at simulation time of 13 sec. For RMRYF the throughput is 0.20 data packets/sec initially and stabilizes at 0.46 data packets/sec at simulation time of 14 sec. For RMRCF the throughput is 0.85 data packets/sec in the beginning and varies till simulation time of 12 sec to become constant at 0.69 data packets/sec. For RMWBF and RMLNF the throughput varies in the range of [0.53-0.56] and [0.41-0.40] data packets/sec respectively. For RMGMF the throughput is 0.81 data packets/sec initially that fluctuates to stabilize at 0.81 data packets/sec finally. Thus, in case of AT it has been concluded that the RMLNF indicates the lowest and the RMSINR shows the highest throughput.

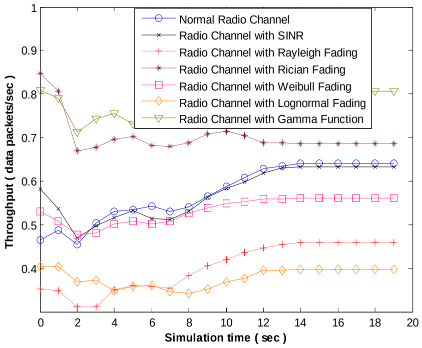


Figure 7. Throughput Comparison of Different Radio Models for Adaptive Tree Protocol

Fig.8 indicates that the lifetime of the AT protocol is 1998 years initially and decreases to 1992 years till simulation time of 13 sec and stabilizes for NRM. For RMSINR the lifetime is 1998 years initially which then decreases to 1991.5 years at simulation time of 13 sec and stabilizes. For RMRYF the lifetime is 1998 years initially and stabilizes at 1992.5 years at simulation time of 13 sec. In case of RMRCF, RMWBF, RMLNF and RMGMF the lifetime varies in the range of [1998-1990], [1998.5-1995], [1996.5-1978] and [1998.5-1996.5] years respectively.

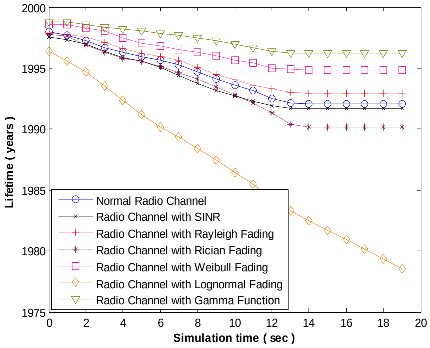


Figure 8. Lifetime Comparison of Different Radio Models for Adaptive Tree Protocol

Thus, in case of AT it is evident that the RMLNF shows the lowest (3 years) and the RMGMF indicates the highest (21.5 years) lifetime amongst all the radio models. The lifetime predicts a decrease by 6.0, 6.5, 5.5, 8.0, 3.5, 18.5 and 2.0 years for NRM, RMSINR, RMRYF, RMRCF, RMWBF, RMLNF and RMGMF respectively in case of AT protocol.

5. Conclusion

In this paper, the simulation results of the comparative investigation of the performance of routing protocols CF, RTS and AT using advance wireless sensor simulator Prowler have been presented. It is quite evident from the discussions of the results obtained that the AT protocol has the highest throughput in case of RMGMF while CF protocol has the highest throughput in case of RMSINR. Moreover, the RTS protocol has the highest throughput in case of NRM. The lifetime of AT, CF and RTS protocols is better in case of RMGMF, NRM and RMGMF respectively. Further, amongst the CF, RTS and AT protocols, the throughput for the CF is 2.5 and 6.5 percent greater than RTS and AT respectively. However, the lifetime in case of AT indicates an increase by 12.5 and 14.5 years respectively when compared with RTS and CF. Thus it has been concluded that the AT protocol can be applied to achieve better lifetime in real time for wireless sensor networks.

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