Performance Evaluation of Routing Protocols for WSNs Based on Energy-aware Routing with different Radio Models

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ABSTRACT
In this paper, we present the simulation results of the comparative investigation of the performance of the wireless sensor network routing protocols based on different routing objective: energy-aware routing using PROWLER and RMASE. Our simulation results indicate that the energy-aware routing objective increases the network lifetime for the Adaptive Tree, Constrained Flooding and Real-Time routing protocols than the default shortest path routing objective for Normal Radio Model, Radio Model with SINR, Radio Model with Rayleigh Fading and Radio Model with Rician Fading. It has been concluded that the network lifetime is longer with energy-aware as compared to shortest path routing objective. The energy-aware routing objective o = $e_{max}/(e+1)$ gives better lifetime than o = (k x u) + 1 for CF and AT routing protocols. It has been shown that without changing the routing strategy and by using the right routing metrics routing protocols can be made energy-aware to increase lifetime.

Keywords
Constrained flooding, real-time search, adaptive tree, routing 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].

Routing in sensor network has very different characteristics than that in traditional communication networks. Lot of research has been done recently on routing mechanisms that take QoS specifications into consideration. A new routing metric for energy-aware load balancing to increase lifetime in case of the normal radio model has been proposed in [2]. However, the effect of energy-aware routing objective has been studied in case of normal radio model (NRM) only. In the literature, moreover, it has been found that the performance of WSNs with various routing protocols mentioned above has not been carried out in the presence of realistic fading models. In this work, a new radio model with Rician fading has been developed. Subsequently, the effect of energy-aware routing objective to increase lifetime has been studied in case of radio model with SINR (RMSINR) radio model with Rayleigh fading (RMRYF), radio model with Rician fading (RMRCF) and NRM for constrained flooding, real-time search and adaptive tree protocols.

Thus the main contribution of this paper is an in-depth study of the effect of the energy-aware routing objective in comparison to that of the shortest path routing objective usually used in the wireless sensor networks routing protocols. The comparison has been done on the basis of performance analysis and comparisons of lifetime metric (years) using RMASE (Routing modeling Application Simulation Environment) [3], an application built on PROWLER (Probabilistic Wireless Network Simulator) [4]. Simulation results show that the adaptive tree protocol (AT) [5] can be applied to achieve better energy consumption, efficiency and lifetime in real time as compared to constrained flooding (CF) [6] and real-time search protocol (RTS) [7].

The remainder of the paper is organized as follows. Section 2 describes the simulation model used. Section 3 analyzes the performance of protocols NRM, RMSINR, RMRYF and RMRCF for the CF, RTS and AT protocols. Section 4 concludes the paper.

2. SIMULATION MODEL
In this section, we analyze the performance of the routing protocols using PROWLER and RMASE. The tool is implemented in MATLAB, thus, it provides a fast and easy way to prototype applications and has nice visualization capabilities.

2.1 Radio, MAC and Routing Application 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 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 [8]:

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

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

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 $\sigma_\beta > 0$. In (4), 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:

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

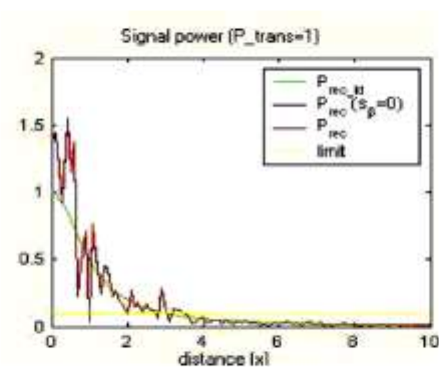
where R is a random variable with exponential distribution (mu=1). The coherence time is tau = 1 sec. Fig.1 (c) shows a snapshot of the radio reception curves in this model.

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

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

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 MAC layer communication is modeled by a simplified event channel that simulates the Berkeley motes' [9] 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*.



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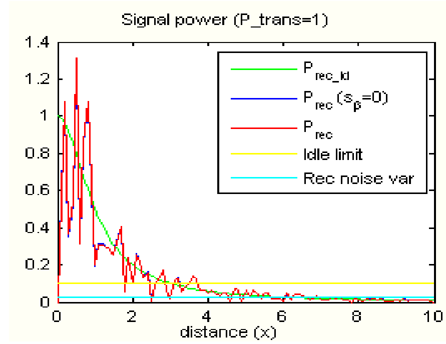

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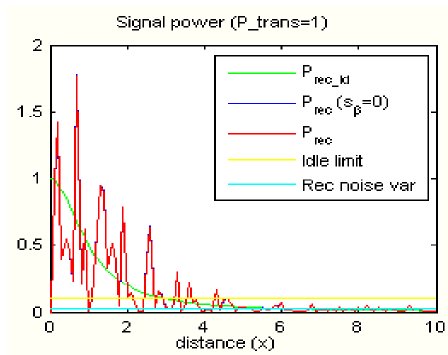

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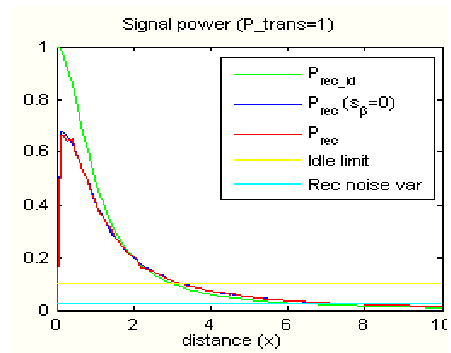


(d)

Fig.1 Snapshot of radio reception curves for (a) NRM (b) RMSINR (c) RMRYF (d) RMRCF

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.

RMASE provides network generation and performance evaluations for routing algorithms. It 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 energy-aware and shortest path protocols. The application, Pursuer Evader Game (PEG) [10], 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.

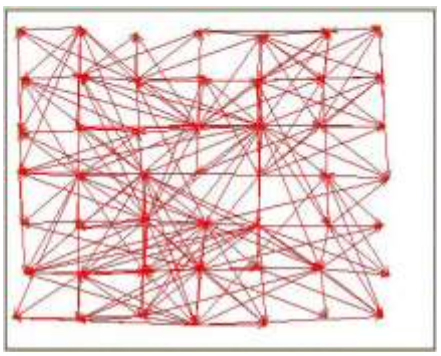


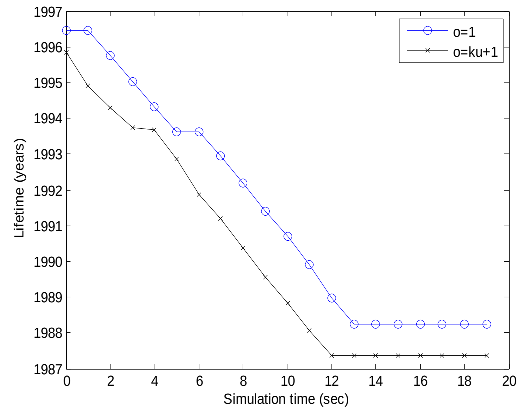
Fig.2 Instance of radio connectivity

The radio data rate is 40 kbps [11] 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.

This section discusses the simulation results of the comparative investigation of the performance of the wireless sensor network routing protocols based on different routing objective: energy-aware routing.

3.1 Case 1: Constrained Flooding (CF)

Fig.3 (a) indicates that the lifetime in case of the CF protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1996 years initially and decreases to stabilize at 1987.5 years at simulation time of 12 sec. On the other hand, the lifetime with shortest-path routing objective is 1996.5 years initially and decreases to stabilize at 1988 years at simulation time of 13 sec. Thus, the energy-aware routing objective o = (k x u) +1 decreases the lifetime of sensor network by half a year. However, in case of energy-aware routing objective o = e_{max}/(e+1) where e_{max} is a constant indicating a maximum energy level (Fig.3 (b)), the lifetime in case of the CF protocol is 1986 years initially and decreases to stabilize at 1971 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1986 years initially and decreases to stabilize at 1968 years at simulation time of 19 sec. Thus, the energy-aware routing objective o = e_{max}/ (e+1) increases the lifetime of sensor network by three years. Therefore, it has been concluded that the lifetime in case of the CF protocol for NRM shows an increase when energy-aware routing objective (o = e_{max}/ (e+1)) is used rather than the energy-aware routing objective (o = (k x u) +1).



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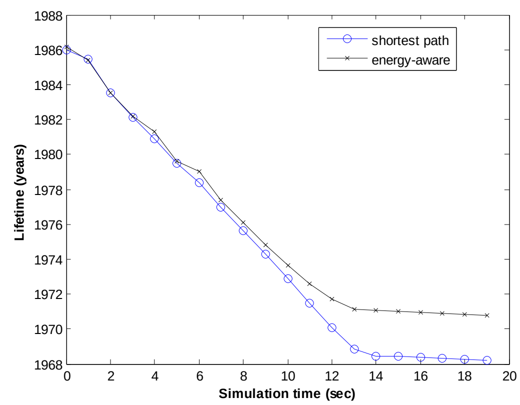
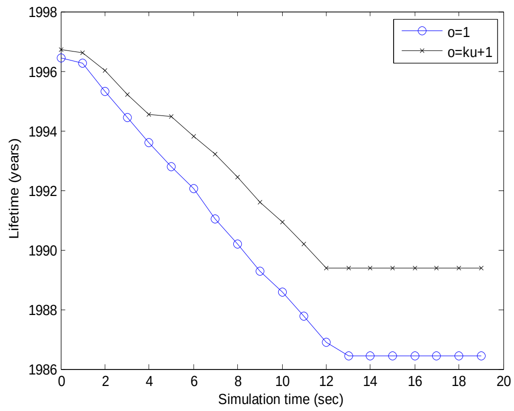


(b)

Fig.3 Lifetime comparison of shortest path & energy-aware routing in case of normal radio channel for constrained flood protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Fig.4 (a) shows that the lifetime in case of the CF protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1997 years initially and decreases to stabilize at 1989.5 years at simulation time of 12 sec. On the other hand, the lifetime with shortest-path routing objective is 1996.5 years initially and decreases to stabilize at 1986.5 years at simulation time of 13 sec. Thus, the energy-aware routing objective o = (k x u) +1 increases the lifetime of sensor network by three years. However, in case of energy-aware routing objective o = e_{max}/(e+1) where e_{max} is a constant indicating a maximum energy level (Fig.4 (b)), the lifetime in case of the CF protocol is 1986 years initially and decreases to stabilize at 1968 years at simulation time of 19 sec. On the other hand, the lifetime with shortest-path routing objective is 1986 years initially and decreases to stabilize at 1967 years at simulation time of 14 sec. Thus, the energy-aware routing objective o = e_{max}/ (e+1) increases the lifetime of sensor network by one year. Therefore, it has been concluded that there is an increase in the lifetime in case of the CF protocol for RMSINR when energy-aware routing objective (o = (k x u) +1) is used rather than the energy-aware routing objective (o = e_{max}/ (e+1)).



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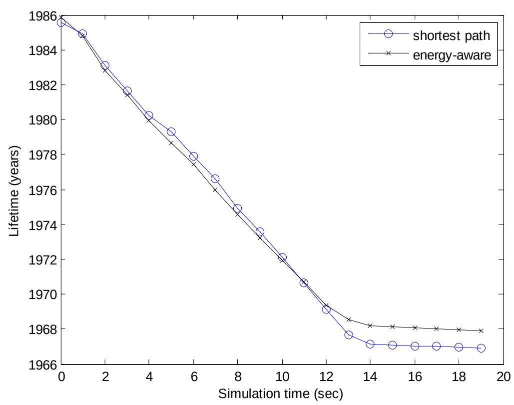

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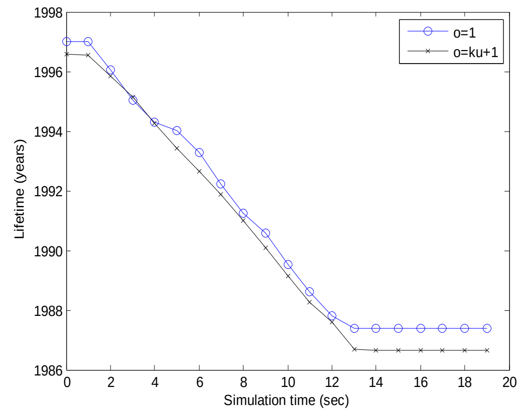
Fig.4 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with SINR for constrained flood protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Fig.5 (a) depicts that the lifetime in case of the CF protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1996.5 years initially and decreases to stabilize at 1986.5 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1997 years initially and decreases to stabilize at 1987.5 years at simulation time of 13 sec. Thus, the energy-aware routing objective o = (k x u) +1 decreases the lifetime of sensor network by a year. However, in case of energy-aware routing objective o = e_{max}/(e+1) where e_{max} is a constant indicating a maximum energy level (Fig.5 (b)), the lifetime of the CF protocol is 1985.5 years initially and decreases to stabilize at 1967 years at simulation time of 19 sec. On the other hand, the lifetime with shortest-path routing objective is 1985.5 years initially and decreases to stabilize at 1966 years at simulation time of 19 sec. Thus, the energy-aware routing objective o = e_{max}/ (e+1) increases the lifetime of sensor network by one year. Therefore, it has been concluded that the lifetime in case of the CF protocol for RMRYF shows an increase when energy-aware routing objective (o = e_{max}/ (e+1)) is used rather than the energy-aware routing objective (o = (k x u) +1).



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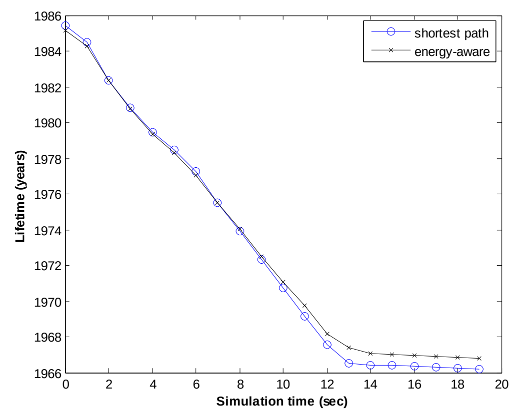

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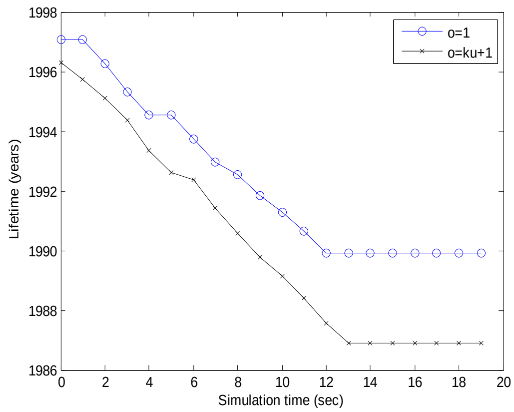
Fig.5 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with Rayleigh fading for constrained flood protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Fig.6 (a) indicates that the lifetime in case of the CF protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1996 years initially and decreases to stabilize at 1987 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1997 years initially and decreases to stabilize at 1990 years at simulation time of 12 sec. Thus, the energy-aware routing objective o = (k x u) +1 decreases the lifetime of sensor network by three years. However, in case of energy-aware routing objective o = e_{max}/ (e+1) where e_{max} is a constant indicating a maximum energy level (Fig.6 (b)), the lifetime of the CF protocol is 1986 years initially and decreases to stabilize at 1969 years at simulation time of 14 sec. On the other hand, the lifetime with shortest-path routing objective is 1986 years initially and decreases to stabilize at 1968 years at simulation time of 19 sec. Thus, the energy-aware routing objective $o = e_{max}/ (e+1)$ increases the lifetime of sensor network by one year. Therefore, it has been concluded that the lifetime in case of the CF protocol for RMRCF shows a significant increase when energy-aware routing objective is ($o = e_{max}/ (e+1)$) than ($o = (k \times u) +1$).



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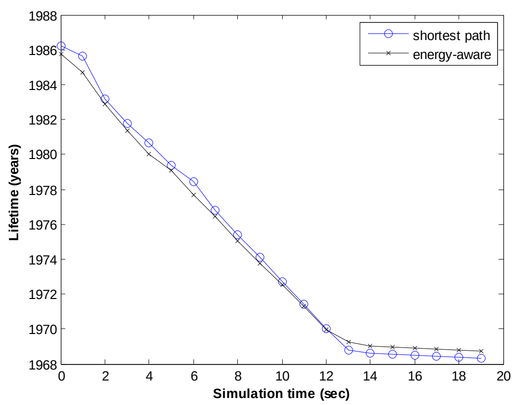

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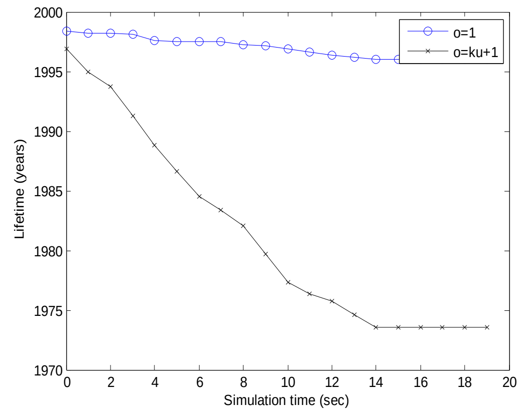
Fig.6 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with Rician fading for constrained flood protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

3.2 Case 2: Real-Time Search (RTS)

Fig.7 (a) shows that the lifetime of the RTS protocol with energy-aware routing objective $o = (k \times u) +1$ where k is a constant = 0.2 and u is the average energy of sensor nodes is 1997 years initially and decreases to stabilize at 1974 years at simulation time of 14 sec. On the other hand, the lifetime with shortest-path routing objective is 1998 years initially and decreases to stabilize at 1996 years at simulation time of 14 sec. Thus, the energy-aware routing objective $o = (k \times u) +1$ decreases the lifetime of sensor network by twenty-two years. However, in case of energy-aware routing objective $o = e_{max}/(e+1)$ where e_{max} is a constant indicating a maximum energy level (Fig.7 (b)), the lifetime of the RTS protocol is 1988 years initially and decreases to stabilize at 1975 years at simulation time of 14 sec. On the other hand, the lifetime with shortest-path routing objective is 1988 years initially and decreases to stabilize at 1975 years at simulation time of 13 sec. Thus, the lifetime of sensor network shows no change with energy-aware routing objective $o = e_{max}/ (e+1)$. Therefore, it has been concluded that the lifetime in case of the RTS protocol in case of NRM does not shows a significant increase when energy-aware routing objective is either ($o = (k \times u) +1$) or ($o = e_{max}/ (e+1)$).



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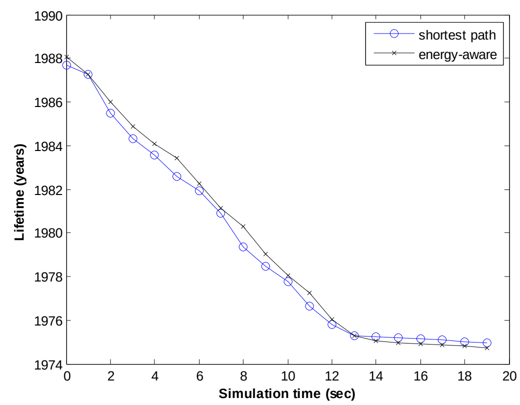
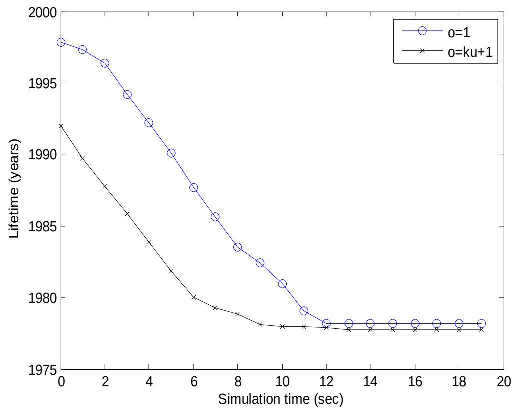


(b)

Fig.7 Lifetime comparison of shortest path & energy-aware routing in case of normal radio channel for real time search protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Fig.8 (a) depicts that the lifetime in case of the RTS protocol with energy-aware routing objective $o = (k \times u) +1$ where k is a constant = 0.2 and u is the average energy of sensor nodes is 1992 years initially and decreases to stabilize at 1978 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1998 years initially and decreases to stabilize at 1978 years at simulation time of 12 sec. Thus, the lifetime of sensor network shows no change with energy-aware routing objective $o = (k \times u) +1$. However, in case of energy-aware routing objective $o = e_{max}/(e+1)$ where e_{max} is a constant indicating a maximum energy level (Fig.8 (b)), the lifetime of the RTS protocol is 1987 years initially and decreases to stabilize at 1972 years at simulation time of 18 sec.



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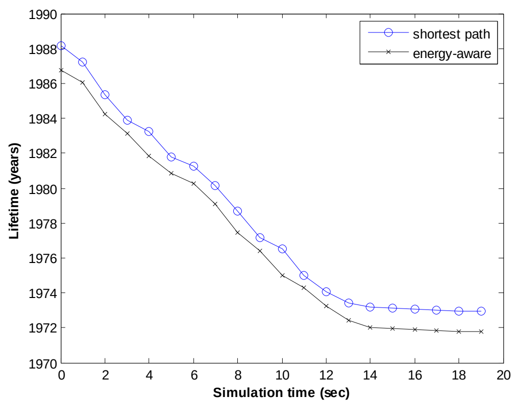
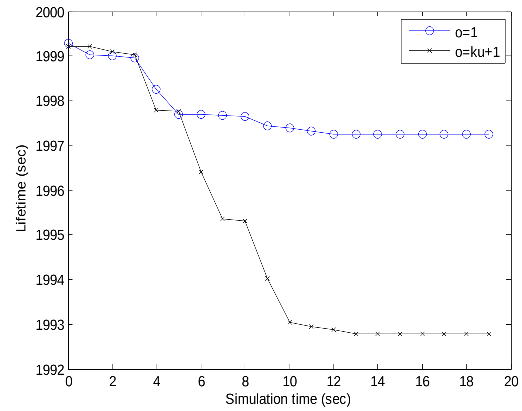


(b)

Fig.8 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with SINR for real time search protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

On the other hand, the lifetime with shortest-path routing objective is 1988 years initially and decreases to stabilize at 1973 years at simulation time of 14 sec. Thus, the energy-aware routing objective (o = e_{max}/ (e+1)) decreases the lifetime of sensor network by one year. Therefore, it has been concluded that the lifetime in case of the RTS protocol for RMSINR does not show a significant increase when energy-aware routing objective is either (o = e_{max}/ (e+1)) or (o = (k x u) +1).

Fig.9 (a) indicates that the lifetime of the RTS protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1999 years initially and decreases to stabilize at 1993 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1999 years initially and decreases to stabilize at 1997 years at simulation time of 12 sec. Thus, the energy-aware routing objective o = (k x u) +1 decreases the lifetime of sensor network by four years. However, in case of energy-aware routing objective o = e_{max}/(e+1) where e_{max} is a constant indicating a maximum energy level (Fig.9 (b)), the lifetime of the RTS protocol is 1988 years initially and decreases to stabilize at 1974 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1988 years initially and decreases to stabilize at 1974 years at simulation time of 13 sec.



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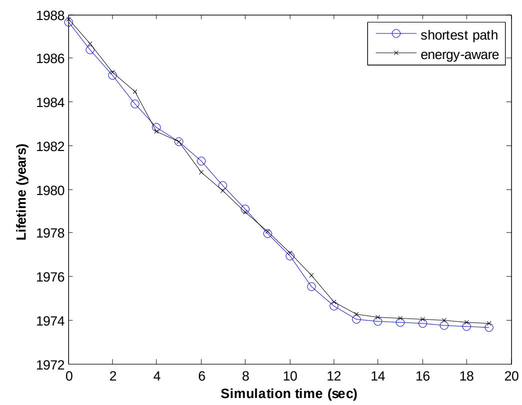

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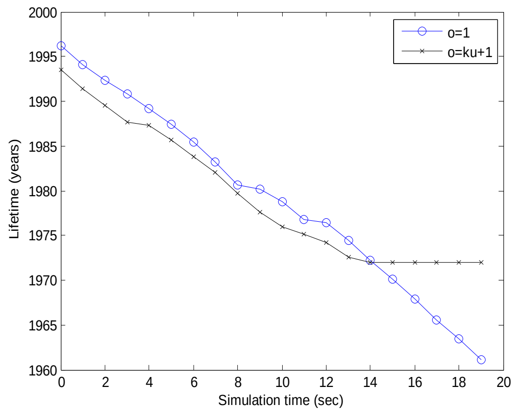
Fig.9 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with Rayleigh fading for real time search protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Thus, the lifetime of sensor network shows no change with energy-aware routing objective o = e_{max}/ (e+1). Therefore, it has been concluded that the lifetime in case of the RTS protocol for RMRYF does not show a significant increase when energy-aware routing objective is either (o = e_{max}/ (e+1)) or (o = (k x u) +1).

Fig.10 (a) shows that the lifetime of the RTS protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1993 years initially and decreases to stabilize at 1972 years at simulation time of 14 sec. On the other hand, the lifetime with shortest-path routing objective is 1996 years initially and decreases to stabilize at 1960 years at simulation time of 19 sec. Thus, the energy-aware routing objective o = (k x u) +1 increases the lifetime of sensor network by twelve years. However, in case of energy-aware routing objective o = e_{max}/(e+1) where e_{max} is a constant indicating a maximum energy level (Fig.10 (b)), the lifetime of the RTS protocol is 1988 years initially and decreases to stabilize at 1971 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1988 years initially and decreases to stabilize at 1970 years at simulation time of 19 sec.



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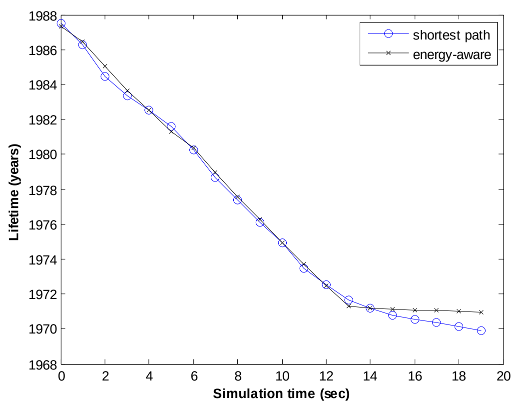

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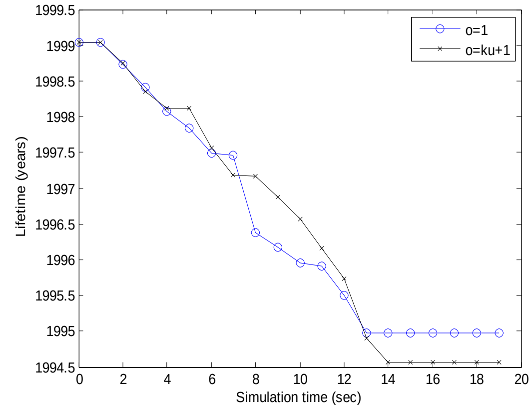
Fig.10 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with Rician fading for real time search protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Thus, the lifetime of sensor network decreases by one year with energy-aware routing objective o = e_{max}/(e+1). Therefore, it has been concluded that the lifetime in case of the RTS protocol for RMRCF shows a significant increase when energy-aware routing objective is (o = (k x u) +1) than (o = e_{max}/ (e+1)).

3.3 Case 3: Adaptive Tree (AT)

Fig.11 (a) depicts that the lifetime of the AT protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1999 years initially and decreases to stabilize at 1994.5 years at simulation time of 14 sec. On the other hand, the lifetime with shortest-path routing objective is 1999 years initially and decreases to stabilize at 1995 years at simulation time of 13 sec. Thus, the energy-aware routing objective o = (k x u) +1 decreases the lifetime of sensor network by half a year.



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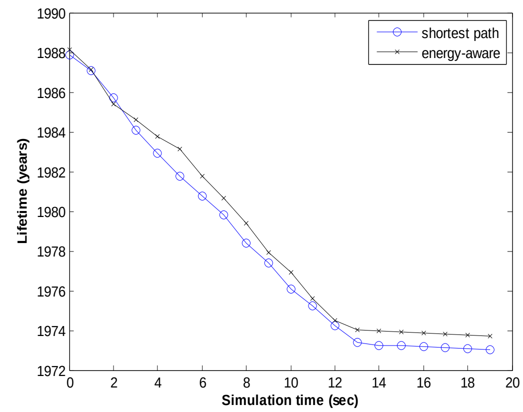

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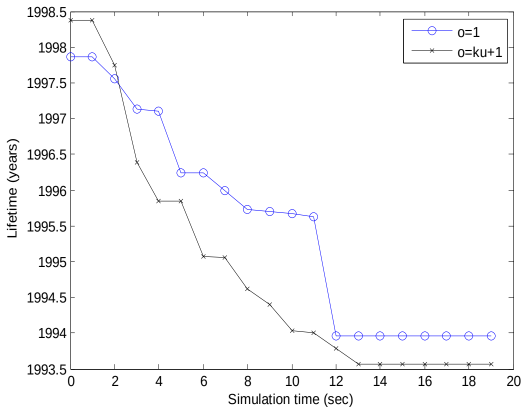
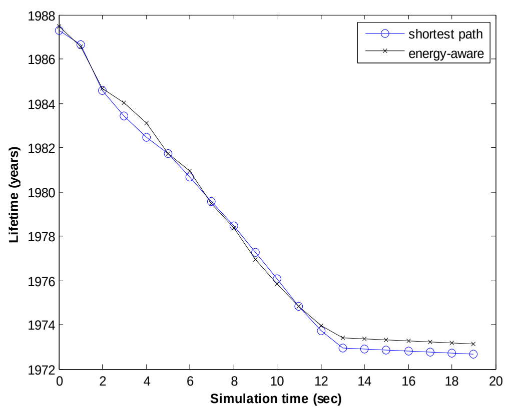
Fig.11 Lifetime comparison of shortest path & energy-aware routing in case of normal radio channel for adaptive tree protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

However, in case of energy-aware routing objective o = e_{max}/(e+1) where e_{max} is a constant indicating a maximum energy level (Fig.11 (b)), the lifetime of the AT protocol is 1988 years initially and decreases to stabilize at 1974 years at simulation time of 19 sec. On the other hand, the lifetime with shortest-path routing objective is 1988 years initially and decreases to stabilize at 1973 years at simulation time of 14 sec. Thus, the lifetime of sensor network increases by one year with energy-aware routing objective o = e_{max}/(e+1). Therefore, it has been concluded that the lifetime in case of the AT protocol for NRM shows a significant increase when energy-aware routing objective is (o = e_{max}/ (e+1)) rather than (o = (k x u) +1).

Fig.12 (a) indicates that the lifetime of the AT protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1998.5 years initially and decreases to stabilize at 1993.5 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1998 years initially and decreases to stabilize at 1994 years at simulation time of 12 sec.



(a)

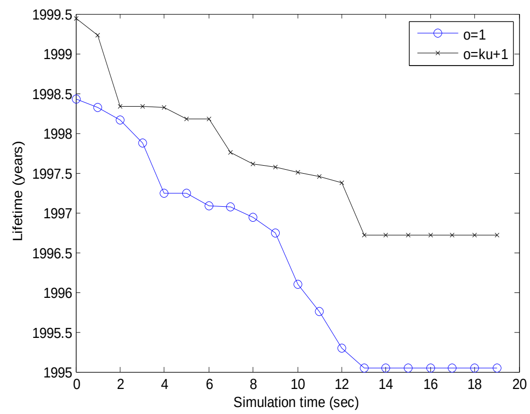


(b)

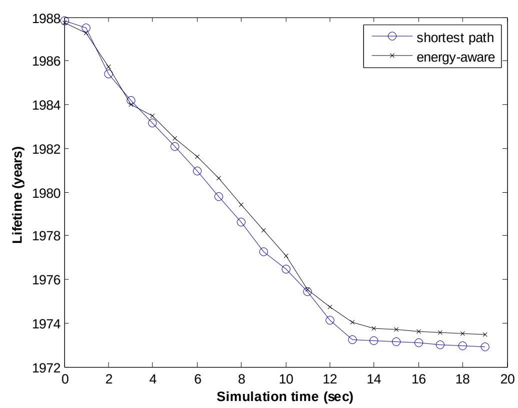
Fig.12 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with SINR for adaptive tree protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Thus, the energy-aware routing objective o = (k x u) +1 decreases the lifetime of sensor network by half a year. However, in case of energy-aware routing objective o = e_{max}/ (e+1) where e_{max} is a constant indicating a maximum energy level (Fig.12 (b)), the lifetime of the AT protocol is 1987 years initially and decreases to stabilize at 1973 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1987 years initially and decreases to stabilize at 1972.5 years at simulation time of 18 sec. Thus, the lifetime of sensor network increases by a year with energy-aware routing objective o = e_{max}/ (e+1). Therefore, it has been concluded that the lifetime in case of the AT protocol for RMSINR shows a slight increase when energy-aware routing objective is (o = e_{max}/ (e+1)) rather than (o = (k x u) +1).

Fig.13 (a) shows that the lifetime of the AT protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1999.5 years initially and decreases to stabilize at 1996.55 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1998.5 years initially and decreases to stabilize at 1995 years at simulation time of 13 sec. Thus, the energy-aware routing objective o = (k x u) +1 increases the lifetime of sensor network by almost two years. However, in case of energy-aware routing objective o = e_{max}/ (e+1) where e_{max} is a constant indicating a maximum energy level (Fig.13 (b)), the lifetime of the AT protocol is 1988 years initially and decreases to stabilize at 1974 years at simulation time of 14 sec. On the other hand, the lifetime with shortest-path routing objective is 1988 years initially and decreases to stabilize at 1973 years at simulation time of 13 sec. Thus, the lifetime of sensor network increases by one year with energy-aware routing objective o = e_{max}/ (e+1). Thus, it has been concluded that the lifetime in case of the AT protocol for RMRYF is better when energy-aware routing objective is (o = (k x u) +1) rather than (o = e_{max}/ (e+1)).



(a)

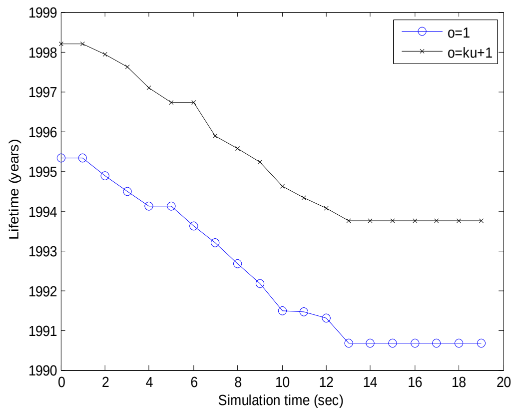


(b)

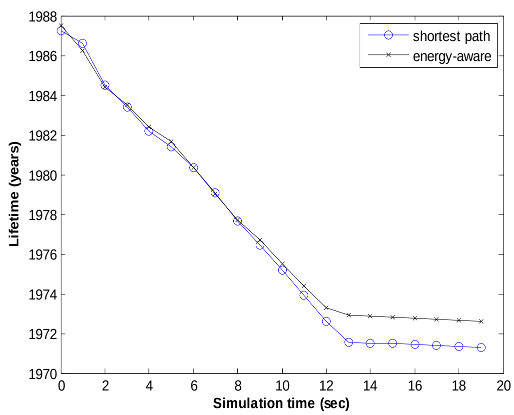
Fig.13 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with Rayleigh fading for adaptive tree protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

Fig.14 (a) depicts that the lifetime of the AT protocol with energy-aware routing objective o = (k x u) +1 where k is a constant = 0.2 and u is the average energy of sensor nodes is 1998 years initially and decreases to stabilize at 1994 years at simulation time of 13 sec. On the other hand, the lifetime with shortest-path routing objective is 1995 years initially and decreases to stabilize at 1991 years at simulation time of 13 sec.

Thus, the lifetime of sensor network increases by three years with the energy-aware routing objective o = (k x u) +1. However, in case of energy-aware routing objective o = e_{max}/ (e+1) where e_{max} is a constant indicating a maximum energy level (Fig.14 (b)), the lifetime of the AT protocol is 1987.5 years initially and decreases to stabilize at 1973 years at simulation time of 14 sec. On the other hand, the lifetime with shortest-path routing objective is 1987.5 years initially and decreases to stabilize at 1971 years at simulation time of 13 sec. Thus, the lifetime of sensor network increases by two years with energy-aware routing objective o = e_{max}/ (e+1). Thus, it has been concluded that the lifetime in case of the AT protocol for RMRCF shows a significant increase when energy-aware routing objective is (o = (k x u) +1) rather than (o = e_{max}/ (e+1)).



(a)



(b)

Fig.14 Lifetime comparison of shortest path & energy-aware routing in case of radio channel with Rician fading for adaptive tree protocol (a) o = (k x u) +1 and (b) o = e_{max}/(e+1)

4. CONCLUSION

This paper presents the simulation results of the comparative investigation of the performance of the wireless sensor network routing protocols based on different routing objective: energy-aware routing. It is evident from the discussions that each of the protocols studied performs well in some cases yet has certain drawbacks in others. The simulation results indicate that the energy-aware routing objective increases the network lifetime for all the three AT, CF and RTS routing protocols than the default shortest path routing. However, in case of the RTS protocol for NRM, RMSINR and RMRYF, the shortest path routing objective gives better lifetime. Moreover, the effect of energy-aware routing objective (o = e_{max}/ (e+1)) on the network lifetime is more profound in case of CF protocol for NRM, RMRYF and RMRCF as well as AT protocol for NRM and RMSINR. Further, the energy-aware routing objective o = (k x u) + 1 enhances the lifetime for CF, RTS and AT protocols in case of RMSINR, RMRCF and RMRYF, RMRCF respectively. It has thus been concluded that the network lifetime is longer with energy-aware as compared to shortest path routing objective. The energy-aware routing objective o = e_{max}/(e+1) gives better lifetime than o = (k x u) + 1 for CF and AT routing protocols.

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