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Research Article

Impact of Mobility on Routing Energy Consumption in Mobile Sensor Networks

Jinman Jung,[1] Yookun Cho,[1] and Jiman Hong[2]

[1] *School of Computer Science and Engineering, Seoul National University, Seoul 151-744, Republic of Korea*
[2] *School of Computing, Soongsil University, Seoul 156-743, Republic of Korea*

Correspondence should be addressed to Jiman Hong, jiman@ssu.ac.kr

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Mobility in mobile sensor networks causes frequent route breaks, and each routing scheme reacts differently during route breaks. It results in a performance degradation of the energy consumption to reestablish the route. Since routing schemes have various operational characteristics for rerouting, the impact of mobility on routing energy consumption shows significantly different results under varying network dynamics. Therefore, we should consider the mobility impact when analyzing the routing energy consumption in mobile sensor networks. However, most analysis of the routing energy consumption concentrates on the traffic condition and often neglects the mobility impact. We analyze the mobility impact on the routing energy consumption by deriving the expected energy consumption of reactive, proactive, and flooding scheme as a function of both the packet arrival rate and topology change rate. Routing energy consumption for mobile sensor networks is analytically shown to have a strong relationship with sensor mobility and traffic conditions. We then demonstrate the accuracy of our analysis through simulations. Our analysis can be used to decide a routing scheme that will operate most energy efficiently for a sensor application, taking into account the mobility as well as traffic condition.

1. Introduction

Mobile sensor networks are dynamic networks formed by a set of mobile sensor nodes and sink node connected through wireless links. These sensor nodes sense a data in application domains (ranging from wildlife monitoring to vehicle tracking) and then transmit the sensed data to the sink node through wireless multihop routing. Sensor nodes have processing and communication capacities, whose main tasks include controlling sensors, processing sensed data, and transmitting the collected data to a sink node. A typical sensor node has a low-power CPU, tiny memory (RAM/ROM), R/F module, many kinds of sensing units, and constrained battery power. For example, Berkeley's MICA motes only have an 8-bit CPU, 4 KB RAM, and only two AA alkaline batteries. The most energy-consuming component is the R/F module, which provides wireless communications. The energy consumption when transmitting 1 bit of data on a wireless channel is similar to thousands of cycles of CPU instructions [1]. Thus, the energy efficiency of the routing schemes for wireless sensor networks largely affects the energy consumption and network lifetime of wireless sensor networks [2].

In recent years, many routing schemes have been proposed. Typically, there are two main categories of routing schemes, proactive schemes (e.g., DSDV [3], SPIN [4]), and reactive schemes (e.g., AODV [5], DSR [6], and MOR [7]). In the proactive schemes, each node periodically sends control packets to the network in order to maintain a routing table. When the network topology changes, the nodes propagate control messages throughout the network in order to update fresh entries in the routing table regardless of the data packets' arrivals. In the reactive schemes, each node sends control packets for route discovery to find the path to the destination only if they are needed, on demand. The reactive scheme can use energy more efficiently than the proactive scheme does for higher mobility. This is because only if a source wants to send to a destination, it invokes the route discovery mechanisms. Meanwhile, the energy consumption of the reactive scheme can increase dramatically under heavy traffic load. If the routing information become frequently inaccurate or stale during the packet transmission, the flooding scheme [8, 9] as a data transfer method can be used.

These various behaviors of the routing schemes according to the mobility and traffic load cause a different pattern in the energy consumption. Hence, knowledge of the characteristics of the network environment such as the mobility and traffic load is necessary when selecting a suitable routing scheme for a specific sensor network application. Fortunately, most sensor networks have some homogeneous characteristics. In a homogeneous network, each node periodically sends its readings to a sink node with the same traffic load in terms of the packet arrival rate, which is the number of sent packets to a sink node per unit time. Additionally, mobility can result from the same network environmental influences (e.g., wind, water, etc.) or the same mobile object (e.g., human, vehicles, etc.) by which the sensors may be carried. Through this assumption, we can approximately estimate the expected mobility variables or know the traffic rate of the sensor networks.

In this paper, we investigate the energy consumption of proactive, reactive, and flooding schemes for various node mobility and traffic loads in terms of the topology change rate and packet arrival rate, respectively. Through analytical evaluation of the energy consumption, we propose a decision mechanism of the routing scheme that will operate most energy efficiently for a sensor application. Our approach is to minimize the energy consumption by modeling the expected energy demands of proactive and reactive schemes as well as flooding scheme. We present the analytical tool needed to compare the energy consumption among the routing schemes.

The remainder of this paper is organized as follows. In Section 2, we present recent works in the modeling of routing schemes for the mobile sensor networks. In Section 3, the system model is described. In Section 4, we derive the expected energy consumption of the routing schemes (i.e., proactive, reactive, and flooding schemes). In Section 5, we analyze the mobility impact on routing energy consumption by comparing proactive, reactive, and flooding schemes. In Section 6, we evaluate the performance of our energy consumption model using a simulation. Finally, additional conclusions are drawn, and potential directions for future work are given in Section 7.

2. Related Works

Several studies on analytical approaches have been proposed for routing schemes [10–15].

Gao [10] presented an analytical approach that showed the characterization of the energy consumption for a sensor network application. However, this work does not cover different characteristics on the performance of the routing protocol.

Yang et al. [11] proposed an analytical model that would ensure the optimal periodic route maintenance for proactive schemes. The authors categorized the proactive protocols based on the periodic route and link maintenance operations done. They focused on the proactive scheme without a comparison of the proactive and reactive schemes, and their model is different from our study in focus of the analysis.

Zhou et al. [12] proposed a mathematical and simulative framework for quantifying an overhead of reactive scheme. They presented a simplified model of OLSR and AODV protocols and studied the scalability of the reactive scheme. However, this work was specific for reactive scheme operating under certain conditions.

Lebedev [13] proposed an analytical tool for a comparison of both the proactive and reactive schemes in the presence of faulty links. In [13], the authors used a different model of energy consumption. Furthermore, the mobility impact was not taken into consideration.

Zhao and Tong [14] proposed an analytical model focusing on the energy consumption in proactive and reactive schemes, delving further into the asymptotic behavior of the routing schemes. One of the goals is to investigate the relationship between the mobility and the energy consumption of the routing schemes, whereas the authors in [14] concentrated on the impact of the traffic conditions.

Xu et al. [15] presented a unified framework for the evaluation of the performance of the proactive and reactive routing schemes. In [15], network configurations varied for the traffic, mobility, and network density for the performance of the reactive or proactive routing schemes. The analysis in [15], however, differs from ours in both the modeling of the energy consumption and the focus of the analysis. For example, the expected energy consumption (J/bit) as shown in our study was not included in the analysis of [15].

3. System Model

3.1. Network Model. We take into consideration a network with N mobile sensor nodes distributed randomly in a square network of size $L \times L$ (see Figure 1). The average node degree, denoted as d, represents the average number of 1-hop neighbors. We assume that all the nodes have the same wireless transmission range r. Two nodes are considered neighbors if they are within the transmission range of one another. We also assume that the channels are error-free and no collisions.

Mobile nodes move according to the random direction mobility model (RDMM) [16]. In this model, mobile nodes choose a random direction and velocity at every epoch. We take into consideration that the number of packets generated at each node is distributed uniformly (λ_p packets per unit time). Each packet contains L_m message bits.

3.2. Energy Model. The energy consumption in the mobile sensor network is categorized as four operating modes: sleep, listening, reception, and transmission. Each node goes to sleep for some time and then wakes up and listens to see if any other node wants to talk to it. The energy consumed by the sleep and listening mode is E_{sleep} (Jules per unit time) and E_{listen} (Jules per bit interval), respectively. When the node detects a transmission from other nodes, it consumes

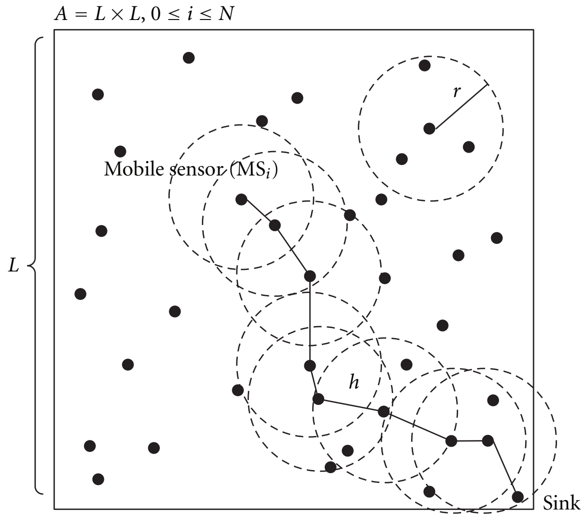


Figure 1: The network model.

Table 1: Energy consumed by reception and transmission. (CC2420, 250 kbps).

Energy	Signal strength (dBm)	Jules per bit (uJ/bit)
E_{tx}	0	0.122
	−1	0.113
	−3	0.105
	−5	0.088
	−10	0.078
	−15	0.069
	−25	0.060
E_{rx}	—	0.140

receiving energy E_{rx} (Joules/bit). The energy consumed by the transmission that covers the neighborhood of a given radius (r) is $E_{tx}(r)$ (Joules/bit). Table 1 shows the energy consumed by the reception and transmission in the case of a CC2420 radio transceiver [17].

3.3. Link Availability and Path Availability. In proactive and reactive schemes, link breaks caused by node mobility lead to the degradation of routing performance by reconstruction and rediscovery in order to update fresh entries in the routing table. As node mobility becomes higher, the likelihood that the link between two nodes will be valid decreases.

The link availability can be defined as the probability that any link between two mobile nodes will be valid from time t_0 to time $t_0 + T$ ($T > 0$) given that they can communicate directly in time t_0. This is given by

$$P\left(T,\varphi_\nu\right) = 1 - \phi\left(\frac{1}{2}, 2, \frac{-4r^2}{\alpha}\right)$$
$$\text{where } \alpha = \frac{4T}{\lambda}\left(\sigma_{\nu^2} + \mu_{\nu^2}\right)\varphi_\nu = \langle \mu_\nu, \sigma_\nu \rangle, \quad (1)$$

where $1/\lambda$ is the mean epoch length for node, and $\phi\ (x, y, z)$ is the Kummer confluent hypergeometric function [18].

For a path with h hops, path availability is the product of the individual link availabilities of the h hops [19]. Therefore, the path availability in terms of the probability that the path with h hops will be valid during time T is given by

$$P_\nu\left(T,\varphi_\nu\right) = \prod_1^h P\left(T,\varphi_\nu\right). \quad (2)$$

Assuming that a significant number of links are involved in a path, the path availability for an h hop path can be simplified to

$$P_h(T,\lambda_c) = \prod_1^h e^{-\lambda_c T} = e^{-\lambda_c h T}, \quad (3)$$

where λ_c is the topology change rate (related to the node mobility [15]). Equation (3) is verified in [19] showing that the path duration distribution can be approximated by an exponential distribution, as the number of hops along a path increases.

By incorporating the path availability in the modeling of the routing schemes, we can study the relationship between node mobility and the routing energy consumption as a probabilistic model. Table 2 shows the notations and functions in this paper.

4. Analysis of the Energy Consumption of the Various Routing Schemes

In this section, we study the expected energy consumed by the proactive, reactive, and flooding schemes while taking into specific consideration the node mobility. To analyze a comparative performance of the routing schemes, we consider a variant routing scheme similar to DSDV [3], AODV [5], and pure flooding [8] for the proactive, reactive, and flooding schemes, respectively.

4.1. Energy Consumption of the Proactive Scheme. We evaluate the expected energy consumption per unit time of the proactive scheme. The expected energy consumption of proactive routing can be expressed by

$$\varepsilon^P\left(\lambda_p,\lambda_c\right) = \varepsilon_{\text{overhead}}\left(\lambda_p,\lambda_c\right) + \varepsilon_{\text{data}}\left(\lambda_p,\lambda_c\right), \quad (4)$$

where λ_p is the packet arrival rate, and λ_c is the topology change rate. In a proactive scheme, the route information is maintained regardless of the packets arrivals. We consider that each node periodically broadcasts its HELLO message which contains their own ID in order to maintain an active neighbor set. The energy consumed by the periodic control traffic (i.e., the HELLO message) can be represented by

$$\varepsilon_{\text{hello}} = L_{\text{id}} \times \left(E_{\text{tx}}(r) + \frac{\pi r^2}{A}(N-1)E_{\text{rx}}\right), \quad (5)$$

where L_{id} is the number of bits for the ID. All neighbor nodes decode the message for each HELLO message transmission. We assume that the average number of neighbors

Table 2: Notations used in this paper.

Notation	Description
N	The total number of nodes.
A	The square area of topology.
d	The average degree of nodes.
r	The effective communication radius.
$E_{\text{tx}}(r),\ E_{\text{rx}},\ E_{\text{listen}}$	The transmission, receiving, and listening energy consumption, respectively.
λ_p	The packet arrival rate at each node which contains L_h header and L_m data bits.
λ_c	The topology change rate experienced by each node in one unit time. The average number of changes in the neighbor set experienced by a node in one unit time.
λ_h	The rate of HELLO message.
$L_{\text{id}}, L_p, L_q, L_e, L_{\text{ack}}$	The bit length of address, RREP, RREQ, RERR, and ACK message, respectively.
h	The number of hops between the source and sink node.
φ_v	The mobility profile which is a set of the mean and standard deviation of node's speed, that is, $\langle \mu_v, \sigma_v \rangle$.
$\varepsilon^P(\lambda_p, \lambda_c)$	The expected energy consumption per unit time of proactive scheme.
$\varepsilon^R(\lambda_p, \lambda_c)$	The expected energy consumption per unit time of reactive scheme.
$\varepsilon^F(\lambda_p, \lambda_c)$	The expected energy consumption per unit time of flooding scheme.
$L\ (\lambda_p, \lambda_c)$	The likelihood function for the decision routing scheme.
T_m	The packet arrival interval for the sink node at each node, that is, $1/\lambda_{\text{p}}$.
$T_d(h)$	The end-to-end delay for a particular h hop active path.

is $\pi r^2/A(N-1)$. And then, if a node detects a change in its neighbor set, the node broadcasts the new neighbor set over the network. When links change, every node exchanges the routing information by means of a DUMP mechanism, as mentioned in [3],

$$\varepsilon_{\text{dump}} = N \times L_{\text{id}} \frac{\pi r^2}{A} N \times \left(E_{\text{tx}}(r) + \frac{\pi r^2}{A}(N-1)E_{\text{rx}} \right), \quad (6)$$

where $L_{\text{id}}(\pi r^2/A)N$ is the number of bits for the routing table of N nodes. We assume that a broadcast DUMP message initiated by a sensor node will reach all the nodes in the networks. Assuming that the rate of the periodic HELLO message is λ_h and the topology change rate is λ_c, we can obtain the expected routing overhead for the proactive scheme by combining (5) and (6). Thus, we have

$$\begin{aligned}
&\varepsilon^P_{\text{overhead}}(\lambda_p, \lambda_c) \\
&\quad = N\lambda_h \varepsilon_{\text{hello}} + N\lambda_c \varepsilon_{\text{dump}} \\
&\quad = N\lambda_h \left\{ L_{\text{id}} \left(E_{\text{tx}}(r) + \frac{\pi r^2}{A}(N-1)E_{\text{rx}} \right) \right\} \\
&\quad\quad + N\lambda_c \left\{ N L_{\text{id}} \frac{\pi r^2}{A} N \left(E_{\text{tx}}(r) + \frac{\pi r^2}{A}(N-1)E_{\text{rx}} \right) \right\}.
\end{aligned} \quad (7)$$

Taking into consideration the number of expected topology changes, the rate of the HELLO messages (λ_h) generated by each node should be more than the topology change rate (λ_c) of the network.

We assume that each sensor node sends λ_p data packets per unit time to a sink node. If a route is found, it immediately sends the data packet. The receiver node sends an acknowledge packet (ACK) as the confirmation of their reception of the packet. Thus, the energy consumed by successful delivery of a data packet is given by

$$\varepsilon_s = (L_h + L_m + L_{\text{ack}}) \times \left(E_{\text{tx}}(r) + E_{\text{rx}} + \frac{\pi r^2}{A}(N-2)E_{\text{listen}} \right) \times h. \quad (8)$$

We consider that a node attempts to retransmit until some maximum number of retransmission (n) in order that conformation is received. The time taken for a message to be transmitted across a path with h hops is assumed to be randomly distributed with a mean value of $T_d(h)$ seconds. The expected energy consumption per unit time of n data retransmission mechanism can be calculated by

$$\begin{aligned}
&\varepsilon_{n-\text{data}}(\lambda_p, \lambda_c) \\
&\quad = N\lambda_p \left\{ \sum_{k=1}^{n} \left((1 - P_h(T_d(h), \lambda_c))^{k-1} \right.\right. \\
&\quad\quad \left. \times P_h(T_d(h), \lambda_c) \left((k-1)\varepsilon_f + \varepsilon_s \right) \right) \\
&\quad\quad \left. + (1 - P_h(T_d(h), \lambda_c))^n n \varepsilon_f \right\} \\
&\quad = N\lambda_p \left\{ \sum_{k=1}^{n} \left\{ (1 - P_h(T_d(h), \lambda_c))^{k-1} \right.\right. \\
&\quad\quad \left. \times P_h(T_d(h), \lambda_c) \left(\frac{\varepsilon_s}{2} k + \frac{\varepsilon_s}{2} \right) \right\} \\
&\quad\quad \left. + (1 - P_h(T_d(h), \lambda_c))^n n \frac{\varepsilon_s}{2} \right\}
\end{aligned}$$

$$= N\lambda_p \frac{\varepsilon_s}{2} \left\{ \sum_{k=1}^{n} \left\{ (1 - P_h(T_d(h), \lambda_c))^{k-1} P_h \times (T_d(h), \lambda_c)(k+1) \right\} + (1 - P_h(T_d(h), \lambda_c))^n n \right\}$$

$$= N\lambda_p \frac{\varepsilon_s}{2} \left\{ \frac{1 - (1 - P_h(T_d(h), \lambda_c))^n}{P_h(T_d(h), \lambda_c)} + 1 - (1 - P_h(T_d(h), \lambda_c))^n \right\}, \quad (9)$$

where $N\lambda_p$ is the average number of packets generated per unit time and $\varepsilon_f = \varepsilon_s/2$. As the maximum number of retransmission goes to infinity ($n \to \infty$), the energy consumed by data retransmission can be obtained as follows:

$$\lim_{n \to \infty} \varepsilon_{\text{data}}\left(\lambda_p, \lambda_c\right) = N\lambda_p \frac{\varepsilon_s}{2} \left(\frac{1}{P_h(T_d(h), \lambda_c)} + 1 \right). \quad (10)$$

A plot for (4) is shown in Figure 2. This plot shows the expected energy consumption of the proactive scheme according to the topology change rate λ_c and the packet arrival rate λ_p for $n = 5$ and $n = \infty$ where $N = 120$, $L = 500$, and $r = 80$. In this figure, we can see that the energy consumed by the proactive scheme increases exponentially as the level of mobility increases due to the data retransmission resulting from unsuccessful delivery. Meanwhile, as the traffic load becomes heavier, the energy consumption increases slightly in a linear fashion. This is because the route information is maintained regardless of the packet's arrivals. Furthermore, the increase by traffic load is significant when mobility is high, due to the retransmission overhead.

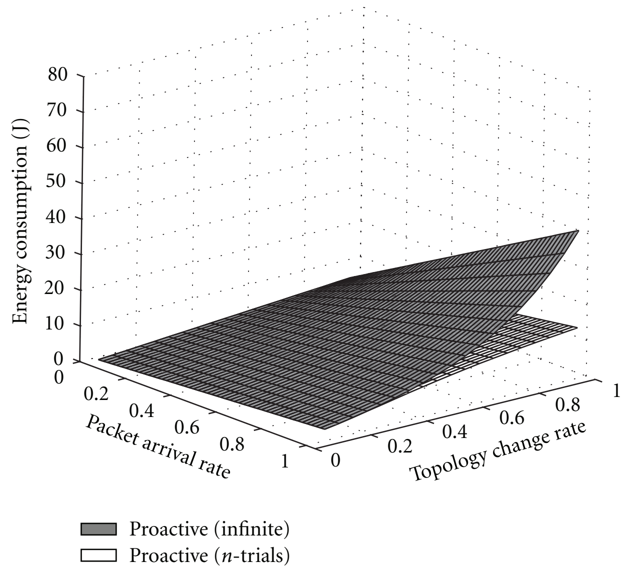


Figure 2: The energy consumption of the proactive scheme.

4.2. Energy Consumption of the Reactive Scheme. The expected energy consumption per unit time of the reactive scheme is the sum of the amount of energy required by the route discovery process and data transmission per unit time

$$\varepsilon^R\left(\lambda_p, \lambda_c\right) = \varepsilon^R_{\text{overhead}}\left(\lambda_p, \lambda_c\right) + \varepsilon_{\text{data}}\left(\lambda_p, \lambda_c\right). \quad (11)$$

When the route path is active in a cached routing table, the node can transmit without the routing overhead. If there is no cached entry in the routing table, the source node initiates a route discovery process by broadcasting a route request (RREQ) packet, which is received and rebroadcasted by other nodes until it reaches its destination. We assume that an RREQ packet will reach almost every node N in the network. Thus, the energy consumed by an RREQ broadcast can be computed as

$$\varepsilon_{\text{rreq}} = N \times L_q \times \left(E_{\text{tx}}(r) + \frac{\pi r^2}{A}(N-1)E_{\text{rx}} \right), \quad (12)$$

where L_q is the number of bits for an RREQ packet. Then, the destination node responds to the RREP back to the source node with a unicast reply mechanism, and as a result, the energy consumed by the RREP is

$$\varepsilon_{\text{rrep}} = L_p \times \left(E_{\text{tx}}(r) + E_{\text{rx}} + \frac{\pi r^2}{A}(N-2)E_{\text{listen}} \right) \times h. \quad (13)$$

However, when a route breakage occurs during the route discovery process, the intermediate node which detects the route breakage returns a route error message (RERR) towards the source node

$$\varepsilon_{\text{rerr}} = L_e \times \left(E_{\text{tx}}(r) + E_{\text{rx}} + \frac{\pi r^2}{A}(N-2)E_{\text{listen}} \right) \times h. \quad (14)$$

To describe the traffic condition in the mobile sensor network, the interarrival intervals of the data packets in the sensor nodes are assumed to be fixed as T_m (i.e., $1/\lambda_p$). If a path for the sink node is valid during T_m, the sensor node immediately begins to forward a data packet to the sink node without a route discovery process. Unless the path is valid, the node reinitiates a route discovery process by first sending an RREQ. Since $N\lambda_p$ route request produced every unit time can cause consecutive discovery process trials, the amount of energy required by the overhead for the reactive scheme is given by

$$\varepsilon^R_{\text{overhead}}\left(\lambda_p, \lambda_c\right) = N\lambda_p \left\{ (1 - P_h(T_m, \lambda_c)) * \varepsilon_{m-\text{discovery}}(m, T_d(h), \lambda_c) \right\}. \quad (15)$$

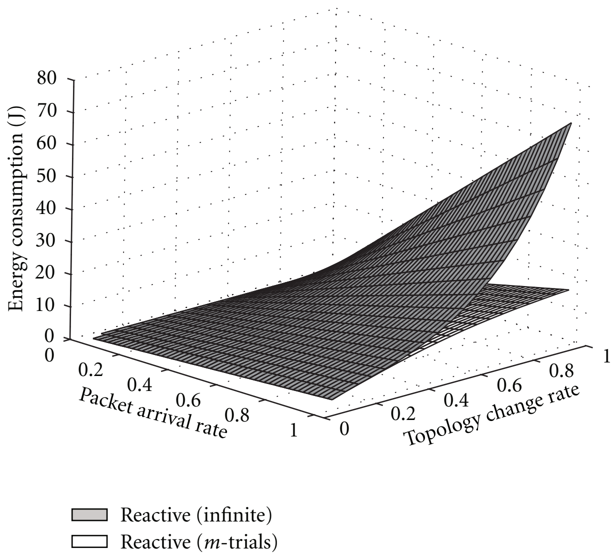


Figure 3: The energy consumption of the reactive scheme.

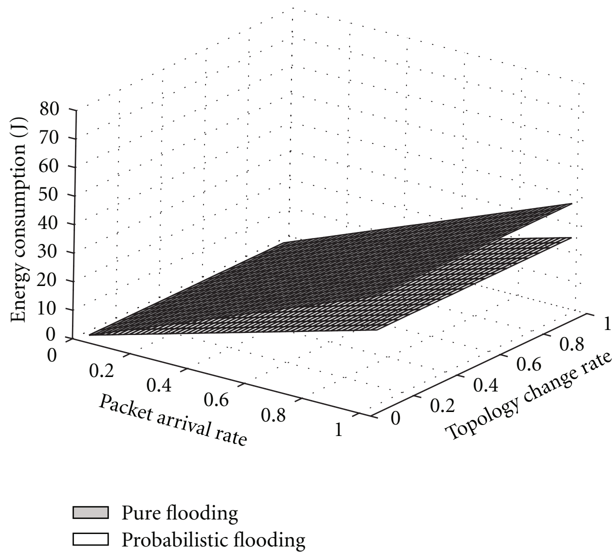


Figure 4: The energy consumption of the flooding scheme.

If an RREP is not received within a certain period, the source node rebroadcasts the RREQ with some maximum number of retransmission attempts (m)

$$\begin{aligned} &\varepsilon_{m-\text{discovery}}(m, T_d(h), \lambda_c) \\ &\quad = \sum_{k=1}^{m} \Big\{ (1 - P_h(T_d(h), \lambda_c))^{k-1} P_h(T_d(h), \lambda_c) \\ &\qquad \times \Big(k\varepsilon_{\text{rreq}} + (k-1)\Big(\frac{\varepsilon_{\text{rrep}} + \varepsilon_{\text{rerr}}}{2}\Big) + \varepsilon_{\text{rrep}} \Big) \Big\} \\ &\quad = \sum_{k=1}^{m} \Big\{ (1 - P_h(T_d(h), \lambda_c))^{k-1} P_h(T_d(h), \lambda_c) \\ &\qquad \times \Big(k\varepsilon_{\text{rreq}} + k\varepsilon_{\text{rrep}} \Big) \Big\} \\ &\quad = \Big(\varepsilon_{\text{rreq}} + \varepsilon_{\text{rrep}}\Big) \sum_{k=1}^{m} k (1 - P_h(T_d(h), \lambda_c))^{k-1} \\ &\qquad \times P_h(T_d(h), \lambda_c) \\ &\quad = \Big(\varepsilon_{\text{rreq}} + \varepsilon_{\text{rrep}}\Big) \Big(\frac{1}{P_h(T_d(h), \lambda_c)} \\ &\qquad - \frac{(1 - P_h(T_d(h), \lambda_c))^m}{P_h(T_d(h), \lambda_c)} \\ &\qquad - m(1 - P_h(T_d(h), \lambda_c))^m \Big), \end{aligned} \tag{16}$$

where m is the maximum number of retransmission attempts.

Assuming that the route discovery process continues until the source node successfully receives the RREP reply, we can simplify the energy consumption for a discovery process to

$$\lim_{m \to \infty} \varepsilon_{m-\text{discovery}}(m, T_d(h), \lambda_c) = \frac{\Big(\varepsilon_{\text{rreq}} + \varepsilon_{\text{rrep}}\Big)}{P_h(T_d(h), \lambda_c)}. \tag{17}$$

Thus, this retransmission procedure is expected to contribute immensely to the energy consumption. After the discovery processes, the node transmits the buffered data packets based on the routing table. We consider that the energy consumed by the data transmission is the same as (15) in the proactive scheme.

A plot for the expected energy consumed unit time by the reactive scheme can be described as a function of the topology change rate λ_c and packet arrival rate λ_p as illustrated in Figure 3. In the reactive scheme, as the traffic load becomes heavier, the increase of energy consumption is greater than that of the proactive scheme. This is largely due to the repetitive RREQ attempts in addition to the data retransmissions. RREP loss due to high mobility leads to degradation of the reactive scheme.

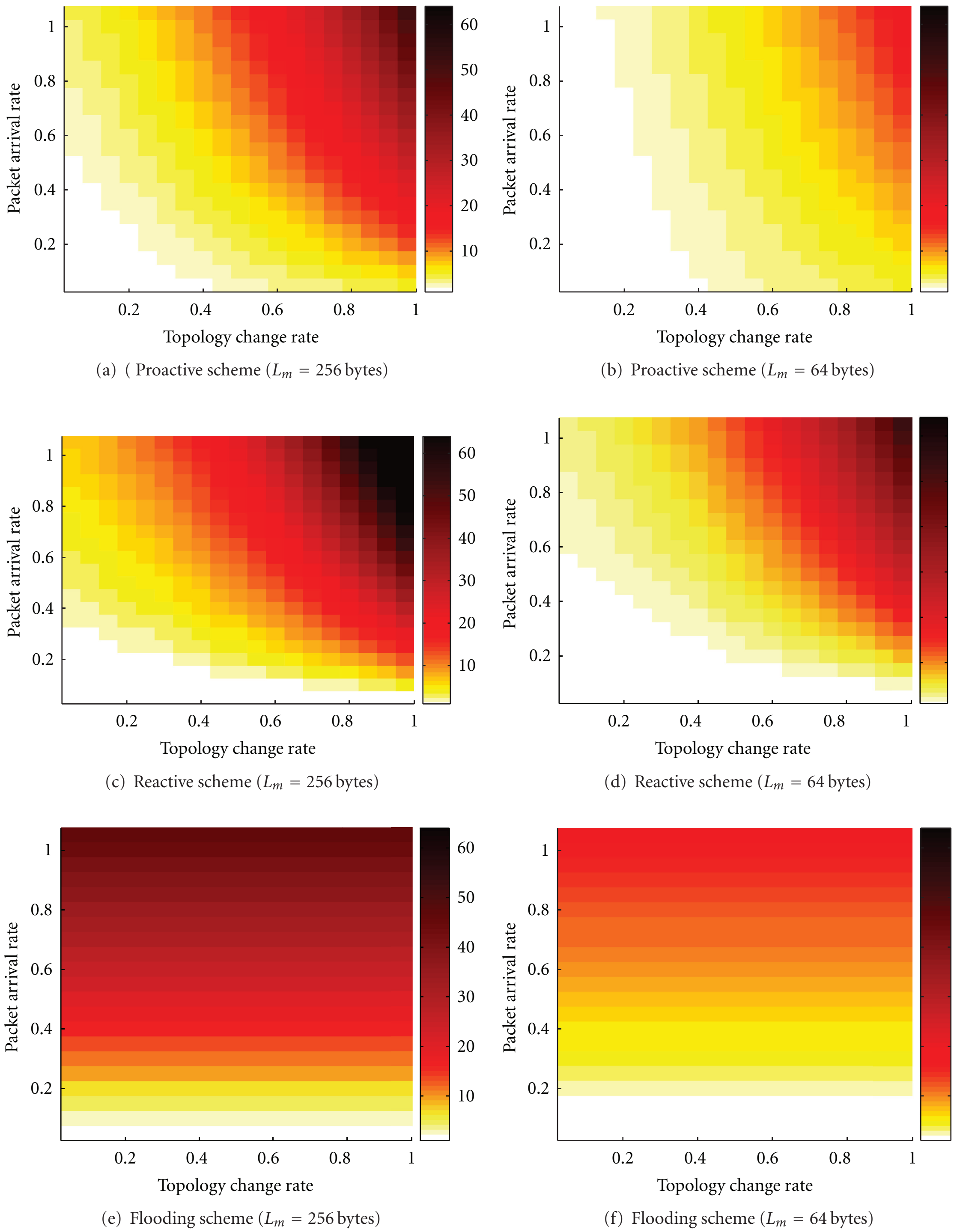
4.3. Energy Consumption of the Flooding Scheme. To analyze the energy consumption of the flooding mechanism, we start with the case of pure flooding ($\varepsilon_{\text{pure}}$) in which all the nodes rebroadcast messages when a node receives a packet for the first time [8]. We assume that a broadcast packet initiated by a source node will reach the other nodes in the network. As the average number of packets generated per unit time in the network is $N\lambda_m$, the expected energy consumed per unit time in the entire network is given by

$$\begin{aligned} &\varepsilon^F\Big(\lambda_p, \lambda_c\Big) \\ &\quad = N\lambda_p \Big\{ N \times (L_h + L_m) \times \Big(E_{\text{tx}}(r) + \frac{\pi r^2}{A}(N-1)E_{\text{rx}} \Big) \Big\}, \end{aligned} \tag{18}$$

where $(L_h + L_m)$ is the size of the flooded packet. Additionally, we can consider the energy consumption of a probabilistic flooding mechanism [8] in which messages are rebroadcast with a certain fixed probability

$$\begin{aligned} &\varepsilon^F\Big(\lambda_p, \lambda_c\Big) \\ &\quad = N\lambda_p \Big\{ P_f \times N \times (L_h + L_m) \times \Big(E_{\text{tx}}(r) + \frac{\pi r^2}{A}(N-1)E_{\text{rx}} \Big) \Big\}, \end{aligned} \tag{19}$$

where P_f is the fixed probability.



(a) (Proactive scheme (L_m = 256 bytes)

(b) Proactive scheme (L_m = 64 bytes)

(c) Reactive scheme (L_m = 256 bytes)

(d) Reactive scheme (L_m = 64 bytes)

(e) Flooding scheme (L_m = 256 bytes)

(f) Flooding scheme (L_m = 64 bytes)

Figure 5: The energy consumption pattern according to the topology change rate and packet arrival rate.

Figure 4 shows the plot of the expected energy consumption of the pure flooding and the probabilistic flooding schemes. Since the flooding-based routing scheme has no routing information, the energy consumption of the flooding scheme is independent of the mobility pattern.

5. The Mobility Impact on Routing Energy Consumption

In the previous section, we investigate the probabilistic energy consumption model for the proactive, reactive, and

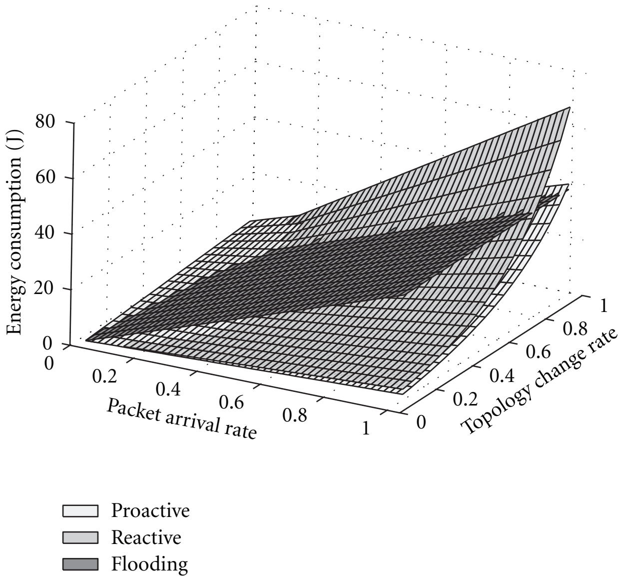


Figure 6: The comparison of the energy consumption of the routing schemes.

flooding schemes in mobile sensor networks. The results described in the previous section provide some insight into the notion that each routing scheme reacts differently during link failures. In this section, we analyze the impact of mobility on the energy consumption of the routing schemes under various networks configurations. Our routing decision approach is designed to select the most energy-effective routing schemes by finding the routing scheme i that minimizes the energy consumption $\varepsilon_i(\lambda_p, \lambda_c)$ for an energy-constrained sensor application, which is shown as follows:

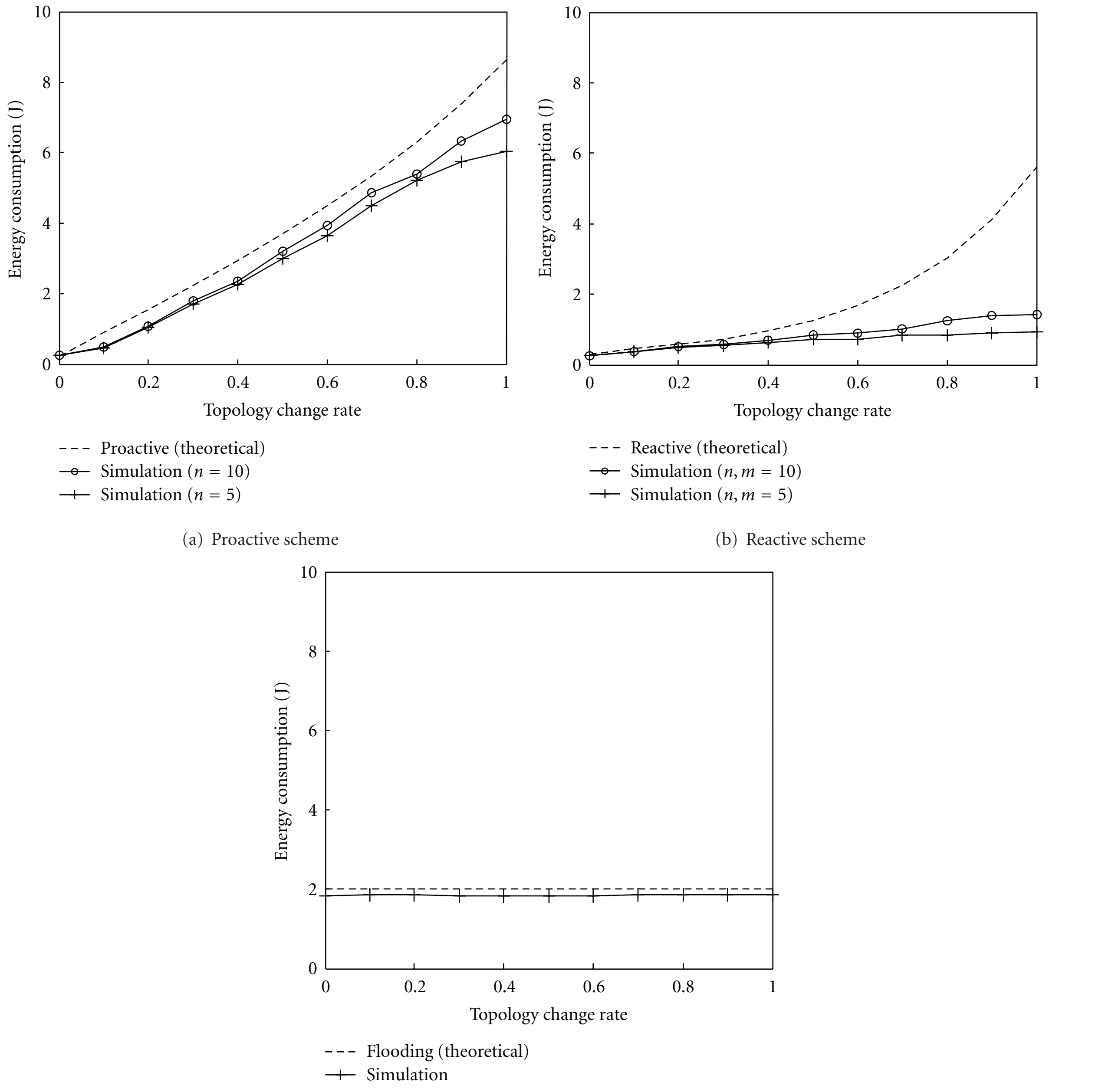
$$D\left(\lambda_p, \lambda_c\right) = \underset{i \in \{F,P,R\}}{\arg\min}\, \varepsilon_i\left(\lambda_p, \lambda_c\right). \tag{20}$$

Figure 5 shows a different energy consumption pattern according to the topology change rate and packet arrival rate for the proactive, reactive, and flooding schemes where $N = 120$, $L = 500$, and $r = 80$. The level of shade toward black means the higher energy consumption. For fairness of routing comparison, we assume the infinite discovery process (as given in (17)) for the reactive scheme. In addition, we consider that the length of the data packet is small (256 bytes, 64 bytes) for the mobile sensor networks [20]. This energy consumption pattern brings out some important characteristic differences between the routing schemes. Our findings show that an increase in the energy consumption is noted as the topology change rate increases in the proactive and reactive schemes. This result was highly expected, since previous studies have come to similar conclusions. However, one of our contributions is to analyze the difference in the energy consumption pattern between the proactive and reactive schemes by comparing the overhead due to the periodic control traffic with that caused by the route discovery. In a proactive scheme, whenever the current route is broken, the control overhead of the route maintenance will be flooded due to continuous route updating. In a reactive scheme, the frequent changes of the topology can lead to the establishment of broken routes which can cause the repetitive route discovery process. Meanwhile, the energy consumption of the flooding scheme is independent of mobility, as illustrated in Figures 5(e) and 5(f). When the traffic load is heavier and the node mobility is lower, the proactive scheme consumes relatively less power. In contrast, when the traffic load is lighter and the node mobility is higher, the reactive scheme is more beneficial. If mobility is much higher, both the proactive and reactive schemes can be useless. In this case, the flooding scheme can be more efficient compared to both the proactive and reactive schemes. Especially, we can see that the flooding scheme performs the best among the evaluated schemes when the length of the data is small ($L_m = 64$ bytes) and the rate of information transmission is low ($\lambda_p < 0.1$), as shown in Figures 5(b), 5(d), and 5(f). For highly dynamic networks, designing an energy-conserving routing scheme is an important issue because the flooding scheme is inherently expensive in energy cost.

We also observe that the reactive scheme is more sensitive to the topology change rate than the proactive scheme as the traffic load increases. In proactive scheme, the control messages such as DUMP or INCREMENT [3] are not retransmitted. However, in the reactive scheme, the control messages such as RREQ are retransmitted for a limited number of times if an RREP is not received within a certain interval. Due to an increase in such retransmissions, the energy consumption of reactive scheme significantly increases as both the packet arrival rate and the topology changes rate increase. This means that the increase of energy consumption caused by a repetitive route discovery process can be greater than that of the periodic control traffic when the mobility is higher. From Figures 5(c) and 5(d), the sensitivity to the mobility is less as the message length is smaller in reactive scheme. A more extensive performance comparison of the proactive, reactive, and flooding schemes can be found in Figure 6. Our analysis can be used to decide a routing scheme that will operate most energy efficiently for a sensor application, taking into account the mobility as well as traffic condition.

6. Simulation

We compare the analytical results obtained in Section 4 against simulation results. We initially consider 120 nodes initially randomly distribute in a square area with a size of 500 m × 500 m. Each node has the same transmit power of coverage of 80 m. After the initial placement, nodes keep moving continuously according to the RDMM model where every node is moving at the same constant speed and only its direction is changed. The topology change rate is estimated from the velocity by heuristic method. The traffic of the activated nodes is set to be the constant bit rate (CBR) with a packet size of 256 bytes. We consider that the energy consumption of reception and transmission for the sensor nodes is equal to the case of a CC2420 radio transceiver [17]. For each configuration, a simulation result is obtained from ten random runs. In addition, since we are interested in the



(a) Proactive scheme

(b) Reactive scheme

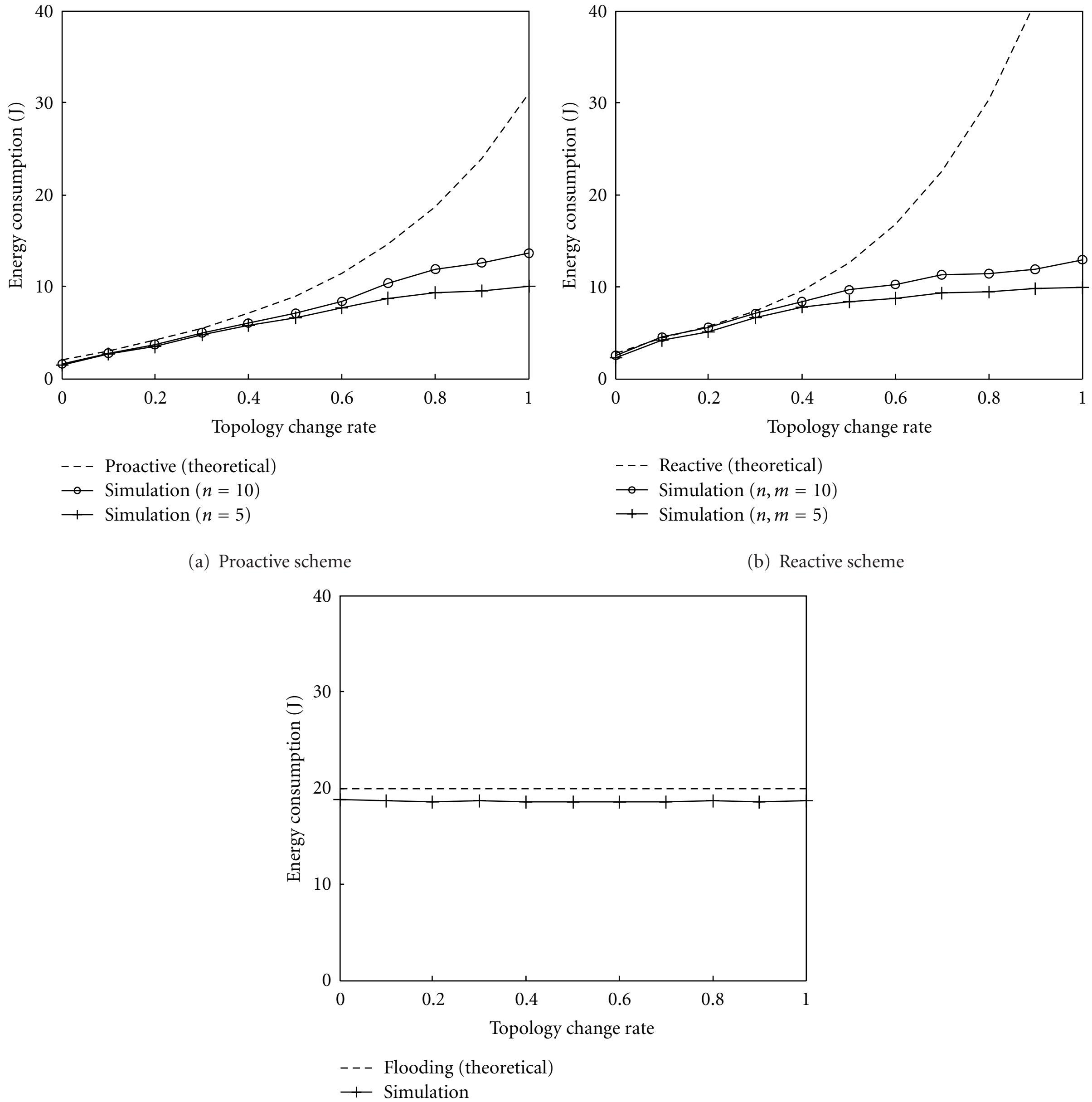
(c) Flooding scheme

Figure 7: Comparison of analytical and simulation results under light traffic load (λ_p = 0.05).

steady state, we ignore the simulation data earlier than 3 seconds from the start time.

We use the NovaSim simulator [21] and compare the proactive ($n = 5$, 10), reactive ($n = 5$, 10 and $m = 5$, 10), and flooding schemes (pure, probabilistic) for the various topology change rates and the packet arrival rates. One of our goals is to analyze the difference in the energy consumption pattern between the proactive and reactive schemes by comparing the overhead due to the periodic control traffic with that caused by the route discovery. Table 3 shows some of the important simulation parameters.

Figure 7 shows the comparison of the energy consumption under light traffic load ($\lambda_p = 0.05$). As shown in Figure 7(a), the proactive scheme is dominated by maintaining periodically the routing table no matter if the nodes need them or not. The reactive scheme, on the other hand, finds a route only when the node needs to send. It seems that the reactive scheme performs the best in all cases in terms of energy consumption. However, taking into account the packet delivery ratio, the reactive scheme becomes the worst one at higher mobility ($\lambda_c > 0.8$). This is because consecutive RREQ attempts are to fail and the



(a) Proactive scheme

(b) Reactive scheme

(c) Flooding scheme

Figure 8: Comparison of analytical and simulation results under heavy traffic load ($\lambda_p = 0.5$).

source node will drop the packet. A frequent change in the topology causes the RREP to possibly not arrive at the node. It can be observed in Figure 7(b) that the initial energy consumption is dependent on the packet arrival rate and becomes saturated as the topology change rate increases. In fact, the number of packet drops increases drastically at $\lambda_c > 0.5$. The discrepancies between the analytical results and the corresponding simulation results in shown Figures 7(a), 7(b), 8(a), and 8(b) are mainly due to the fact that we use a limited number of retransmissions for the RREQ and data packets. Thus, the larger n or m is, the less the discrepancy is.

Figure 8 depicts the comparison of energy consumption at the heavy traffic load ($\lambda_p = 0.5$). When the traffic load is heavy, the proactive scheme outperforms the reactive scheme for $\lambda_c < 0.4$ as shown in Figures 8(a) and 8(b). This is because the reactive scheme is more sensitive to the topology change rate than the proactive scheme as the traffic load increases, as mentioned in Section 5. We can predict that the packet delivery rate of the proactive scheme also increases drastically at $\lambda_c > 0.4$ from the discrepancy between the analytical and simulation results in Figure 8(a). As a result, the proactive scheme performs well under a heavy traffic load for $\lambda_c < 0.4$

Table 3: Parameters used in the simulation.

Parameter	Configuration
Size of field (A)	$500 \times 500\,\text{m}^2$
Distribution of nodes	Random distribution
Number of nodes (N)	120
Transmission range (r)	80 m
Data packet size	256 bytes
Mobility model	RDMM
Traffic load	Constant bit rate
Propagation model	Free space model
Energy consumption	CC2420

and $\lambda_p = 0.5$. However, when $\lambda_c > 0.4$, both the proactive and reactive schemes can be useless due to the packet drops. The energy consumed by the flooding scheme is independent of the topology change rate, as shown in Figures 7(c) and 8(c) for all λ_c.

7. Conclusion and Future Works

We analyzed the energy consumption of the proactive, reactive, and flooding schemes. Through the analysis, it was that the performance of the routing schemes in terms of energy consumption had a strong correlation between mobility and traffic conditions. We also presented a comparative performance analysis of the routing scheme in terms of energy efficiency. A routing scheme can be determined by a range of network parameters, such as the packet arrival rate and topology change rate (related to node mobility). For the sake of validity, we demonstrated the accuracy of our approach through simulations. Our proposed approach presents an energy consumption framework that helps to strengthen and deepen our understanding of the effect of mobility and traffic load on routing schemes.

In our future work, we will focus on analyses that are more sophisticated by considering the devices characteristics for the sensing, processing, and communication units. In addition, we will study an energy-efficient algorithm to dynamically switch the routing protocols between proactive, reactive, and flooding schemes according to the mobility as well as traffic conditions.

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