SEER: Scalable Energy Efficient Relay Schemes in MANETs

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Abstract. In Mobile Ad Hoc Networks (MANETs), *broadcasting* is widely used to support many applications. Several adaptive broadcast schemes have been proposed to reduce the number of rebroadcasting, and can consequently reduce the chance of contention and collision among neighboring nodes. In practice, broadcasting is power intensive especially in dense networks. Thus, a good energy-efficient relay scheme should be able to further maximize the system lifetime without sacrificing the reachability of broadcasting. In this paper, we propose two Scalable Energy Efficient Relay (SEER) schemes that use probabilistic approaches to achieve higher performance and to prolong the system lifetime. In the schemes, each node uses some energy-based heuristic method to independently determine an appropriate rebroadcast probability. Nodes with more residual energy are responsible for forwarding more broadcast messages. One important feature is that such heuristic knowledge is obtained by self-contained local operation. To further improve the effectiveness of broadcasting, we also study how to dynamically adjust the rebroadcast probability according to node mobility. The simulation results show that our proposed approach outperforms the related scheme when the number of broadcast messages, broadcast reachability, and system lifetime are taken into consideration altogether.

1 Introduction

A mobile ad hoc network (MANET) is defined as a collection of mobile nodes where each node is free to move around. In a MANET, broadcasting is an important communication operation for route discovery, address resolution, and many other network services. For instance, on-demand routing protocols such as AODV [9] and DSR [4] use the broadcast operation to disseminate control packets (e.g., the request of discovering a new route to a destination) for maintaining routing-related information at each node. The most straightforward way of broadcasting is by flooding. However, the radio signals are likely to overlap with each other in a geographical area. Broadcasting by blind flooding suffers from the increasing of serious redundancy, contention, and collision, which is known as a broadcast storm problem [8].

Some works [2], [8], [11] have investigated to improve the effectiveness of broadcasting in MANETs. Despite the optimization effort to reduce rebroadcast messages, the approaches mentioned above fail to take energy issues into consideration. The following requirements concerning how to consume energy in an efficient way are important in broadcast protocols. First, it should minimize the number of rebroadcast messages on one hand, while still maintaining good latency and reachability on the other hand. Then, energy consumption situation should be considered at each node when making decisions about whether to rebroadcast the received messages. A simple idea is that nodes with more battery power should be responsible for forwarding more data in behalf of its neighbors. This implies that nodes with lower residual energy can decide to sleep to save their precious energy.

In this paper, we address three important issues on designing an energy-efficient broadcast protocol based on probabilistic schemes. First, the knowledge of global network energy consumption should be available for reference at each node. Here, we use self-contained local operations to approximate the average network energy. Note that nodes should not need to know information about neighbors multiple hops away for our calculating process. Second, each node can compare its residual energy with such maintained energy-based knowledge to determine an appropriate rebroadcast probability based on the principle that nodes with more residual energy are responsible for forwarding more broadcast messages. Third, the rebroadcast probability at a node can be adjusted according to node distribution and node mobility to further improve the effectiveness of broadcasting.

The remainder of this paper is organized as follows: Section 2 gives a brief review of related work. Section 3 presents a detailed description of our SEER schemes. Section 4 provides simulation results to compare the performance of our methods with that of other existing scheme. Finally, conclusions are drawn in Section 5.

2 Related Work

The efficiency of broadcasting protocol can significantly affect the performance of many applications in MANETs. Some works [2], [8], [11] have investigated the inefficiency problem of broadcasting by blind flooding. When node density is high, blind flooding approach may cause (1) redundant transmissions, (2) higher collision rate, and (3) congestion of wireless medium that seriously impair the performance of the entire network. In this section, we briefly review some adaptive broadcast techniques that attempt to minimize the number of rebroadcast messages while maintaining good latency and reachability. These methods can be categorized into three groups: probabilistic, counter-based, and area-based methods.

In simple probabilistic method [8], a mobile node rebroadcasts received messages with a fixed probability P. Clearly, when $P = 1$, this method is equivalent to flooding. [2] follows from results in percolation theory [7] that probabilistic approaches exhibit a certain type of bimodal behavior in sufficiently large networks: in some executions, the broadcast message dies out quickly and hardly any node gets it; in the remaining executions, a substantial fraction of the nodes gets the message. It is also demonstrated that the optimal rebroadcast probability is around 0.65. [11] argues that this value is not likely to be globally optimal and attempt to dynamically adjust the rebroadcasting probability with the node distribution and node movement.

Besides probabilistic methods, Ni et al. [8] introduced a counter-based approach, in which a counter is used to record the number of receiving the same message. A mobile node inhibits the rebroadcast when the counter is larger than a given threshold. The more copies a node receives indicates the higher chance of its neighbors having already received the same message, and more likely it is a rebroadcast redundant. In their approach, a random assessment delay (RAD) is initiated for counting the number of received copies of the current message. It is obvious that this approach is not suitable for delay-sensitive applications. Ni et al. [8] also discussed area-based schemes, including distance-based and location-based approaches. In distance-based approach, a node may hear the same message several times. If the distance to the nearest node is smaller than some distance threshold D, the rebroadcast transmission is canceled. In location-based approach, GPS (Global Positioning System) receivers [5] is used to assist for calculating an additional area. This value is compared to a predefined coverage threshold $A(0 < A < 0.61)$ to determine whether the rebroadcast should be carried on or not.

Although many broadcast protocols have been proposed to reduce redundant rebroadcast messages, most of them do not take energy consumption into account. When several nodes drain of power due to unbalanced energy consumption, it may lead to network partition and shorten the network lifetime. In this paper, we address this problem by combining the probabilistic approaches and energy consumption balancing to maximize the system lifetime while maintaining a high reachability. Our energy-efficient relay schemes adopt the strategy that nodes with more residual energy are responsible for forwarding more broadcast messages. Besides, we also utilize neighbor connectivity information to dynamically determine an appropriate rebroadcasting probability for various network topologies.

3 SEER Design

One solution to maximize long-term network lifetime for frequent broadcast operation over entire network is to inhibit some nodes with lower residual energy from unnecessary rebroadcasting. We present two schemes to do so. In the first scheme, we accumulate a network-wide energy-related knowledge to assist its rebroadcast decision. And, the second scheme further exploits neighbor connectivity information to improve the overall broadcast throughput.

3.1 Network-wide Energy-related Heuristic

Intuitively, for energy conservation purpose, nodes with relatively higher residual energy should be responsible for forwarding more broadcast messages. This implies that nodes with relatively lower residual energy can decide to sleep to save their precious energy. However, in fact, it is hard for a node to accurately determine whether its residual energy is relatively higher or lower than most others. Hence, it is desirable if some network-wide energy-related heuristic can be maintained at each node to help independently distinguish its relative energy level from others. To satisfy the above requirement, we propose an energy-based diffusion algorithm in which each node uses a local operation to approximate the average energy of the entire network, which is called system energy approximation (SEA). A node is called a sub-critical node if its residual energy is less than the SEA value; otherwise, it is called a super-critical node. The algorithm shown below is executed in each node.

Algorithm 1. The Energy-based Diffusion Algorithm

`Initially` *SEA* `:= residual energy level and` *received_SEA_list* `is empty`

1: `for every periodic time interval` t `do`
2:    `if` *received_SEA_list* `is not empty then`
3:       `compute new` *SEA* `by averaging all` *SEA* `values from` *received_SEA_list* `and its residual energy level`
4:    `send` $<SEA>$ `to all neighbors`

5: `upon receiving` $<SEA_i>$ `from a neighbor` n_i
6:    `if` $<SEA_i, n_i>$ `is not in` *received_SEA_list* `then`
7:       `add` $<SEA_i, n_i>$ `to` *received_SEA_list* `with an expiration time`
8:    `else`
9:       `replace it with new` $<SEA_i, n_i>$ `and reset its expiration time`

10: `when an entry` $<SEA_i, n_i>$ `has expired`
11:    `remove this` $<SEA_i, n_i>$ `from` *received_SEA_list*

In Algorithm 1, *SEA* is initially equal to its own residual energy level and the *received_SEA_list* is set to empty. In lines 1 to 4, each node sends the $<SEA>$ message to all neighbors within every time interval t. If the *received_SEA_list* was not empty before sending $<SEA>$ message, the *SEA* value will be recomputed by averaging all *SEA* values from *received_SEA_list* and its residual energy. Upon receiving $<SEA>$ message from a neighbor n_i, the $<SEA, n_i>$ entry will be added to *received_SEA_list* with an expiration time if the $<SEA, n_i>$ entry has not been added yet. Otherwise, replace it with new $<SEA, n_i>$ entry and reset its expiration time (lines 5 to 9). We use the expiration time field to guarantee that the *SEA* value of this entry is fresh. If a node moves away and does not send its *SEA* value before a pre-determined expiration time, its *SEA* value is removed from *received_SEA_list*. To reduce protocol overhead, a node can periodically piggyback <*SEA*> value on the data packet by forwarding.

Initial result about the average-based diffusion algorithm was provided in [6], which gave the convergence proof in mobile environment. The correctness of our energy-based diffusion algorithm follows in the same manner as in the average-based diffusion algorithm, since they have the same averaging operation to approximate a network-wide knowledge. Different from the average-based diffusion algorithm, we feedback the residual energy level to each averaging operation to guarantee the new SEA value can adjust according to the current energy consumption situation of entire network.

3.2 Original SEER Scheme

Our first scheme is based on the basic gossiping protocol proposed by [2]. Our scheme is different from the original gossiping in that only the super-critical nodes need to rebroadcast messages to its neighbors with probability p and discard the received messages without further forwarding with probability $1-p$. A super-critical node rebroadcasts a given message at most once. Hence, if the message has been received again, it is dropped. Note that the sub-critical nodes do not participate in the message forwarding to save the precious energy. This simple scheme is called SEER-1 (p).

Following the results in percolation theory [7], SEER-1(p) exhibits a certain type of bimodal behavior. We assume that all nodes have been initialized their residual energy in a uniform distribution with a given range and let the forwarding probability p of super-critical nodes be equal to 1. As mentioned before, the SEA value obtained at each node approaches to the actual average network energy. The rebroadcast probability of a node in SEER-1(1) is equal to the probability that its residual energy is greater than the SEA value, which is about 0.5.

One problem of SEER-1(p) scheme is how to set the rebroadcast probability p. In SEER-1(1), the rebroadcast probability of each node is around 0.5. Intuitively, this value is not likely to be the globally optimal. For instance, in a denser area, each node has more neighbors whose coverage areas overlap significantly. Rebroadcast messages from nodes in a dense neighborhood will reach the same nodes many times. To reduce such redundancy, the rebroadcast probability in these areas should be set lower. On the contrary, the rebroadcast probability should be set higher in sparse areas to achieve better reachability.

3.3 Adaptive SEER Scheme

As mentioned earlier, only selecting nodes with higher residual energy to participate message forwarding is our primary aim for SEER-1(p). However, using predefined fixed probability p falls in a dilemma between reachability, the number of rebroadcasting messages, and the system lifetime as node movement. It is desirable if the nodes, including both super-critical and sub-critical nodes, can dynamically adjust its rebroadcast probability on-the-fly. In the remainder of this section, we discuss how to optimize the SEER-1(p) scheme by taking connectivity with neighbors into account.

Neighborhood Detection. To dynamically adjust the rebroadcast probability as neighbor connectivity changes, we propose a packet-monitoring-based neighbor detection algorithm to estimate the number of neighbors on-the-fly. Different from the mechanism using periodical HELLO messages, there is no extra message overhead in our algorithm. The pseudocode is shown in Algorithm 2. In lines 1 to 5, each node continuously monitors the incoming broadcast packets and record the number of packets received. For every periodical time interval t at each node, if no broadcast packet p_i is received within t, it updates *nbr_count* with the counter of p_i and removes the entry of p_i from *received_packet_list*.

Algorithm 2. The Packet-monitoring-based Neighbor Detection Algorithm

```
Initially nbr_count := N_d and received_packet_list is empty

1:   upon receiving a broadcast packet p_i
2:      if p_i is not in received_packet_list then
3:          add p_i to received_packet_list with an expiration time
4:      else
5:          increase the received_packet_list[p_i].counter by 1
            // record the number of packet p_i received

6:   for every periodic time interval t do
7:      if no broadcast packet p_i is received within t then
8:          nbr_count := received_packet_list[p_i].counter
9:          remove the entry of p_i from the received_packet_list
```

The packet-monitoring-based neighbor detection algorithm takes time to gradually approach the accurate value of the number of neighbors. If the initial value is set closer to the accurate value, the algorithm will converge to the *nbr_count* faster. Here, we utilize the average network degree to be a basis for initializing the *nbr_count*. Let A be the area of a MANET, N be the number of mobile nodes in the network, and R be the communication range. The average network degree N_d can be obtained by the following formula:

$$N_d = N(\frac{\pi R^2}{A}) - 1 \ . \tag{1}$$

A Three-level Adaptation. The SEER-1(p) uses a fixed rebroadcast probability p for super-critical nodes. According to percolation theory [7], there exists a threshold $P_c < 1$, such that by using P_c as the rebroadcast probability, almost all nodes can receive a broadcast message, and there is no much improvement on reachability for $p > P_c$. Therefore, SEER-1(p) does not work well in various MANET topologies. To give some intuition, we make three observations below.

Observation 1. In a sufficiently large network, only selecting super-critical nodes to rebroadcast received messages suffice to fulfill reachability requirement while achieving higher energy-efficiency, even though all sub-critical nodes decide to sleep to save their precious residual energy.

Observation 2. In a sparse network, a node has fewer neighbors. Some sub-critical nodes are more likely to play a critical role for forwarding messages in order to maintain the connectivity of the network. If they fail to do so, the network is partitioned. Therefore, in addition to super-critical nodes, sub-critical nodes should increase its rebroadcast probability to avoid reachability degradation.

Observation 3. In a dense network, if the neighborhood of a node is crowded enough, we can not only inhibit the sub-critical nodes from forwarding messages but also further decrease the rebroadcast probability of super-critical nodes to reduce redundant transmissions without sacrificing the reachability.

To resolve the dilemma between reachability, the number of rebroadcasting messages, and the system lifetime, we propose a three-level adaptation scheme in which each node can independently adjust its rebroadcast probability according to its residual energy level and the neighborhood status. We extend the fixed probability p into two probability functions Psuper-critical(n) and Psub-critical(n) for super-critical nodes and sub-critical nodes respectively as

$$P_{super-critical}(n) = \begin{cases} 1, & if\ n < n_2, \\ H(n), & if\ n \geq n_2, \end{cases} \tag{2}$$

$$P_{sub-critical}(n) = \begin{cases} 0, & if\ n \geq n_1, \\ L(n), & if\ n < n_1, \end{cases} \tag{3}$$

where n is number of neighbors maintained by our packet-monitoring-based neighbor detection algorithm, H(n) a decrease function within an area $[p_l, 1]$, and L(n) a decrease function within an area [0,1]. Following **Observations 1, 2, and 3**, Fig. 1 shows an abstract shape of three-level adaptation. With few neighbors ($n \leq n1$), not only all super-critical nodes need to rebroadcast but sub-critical nodes should gradually increase their rebroadcast probability if n becomes smaller and smaller. When n is close to 0, we force all nodes to participate messages forwarding for the behalf of reachability. Between n_1 and n_2, no sub-critical nodes need to forward received messages. Only super-critical nodes taking over messages forwarding suffices the broadcasting operation to reach equilibrium state, balancing reachability and power saving. After $n \geq n2$, a decrease function H(n) is used to gradually decrease the rebroadcast probability of super-critical nodes to p_l. Note that p_l is a fixed lower bound for the rebroadcast probability of super-critical nodes to guarantee the reachability requirement.

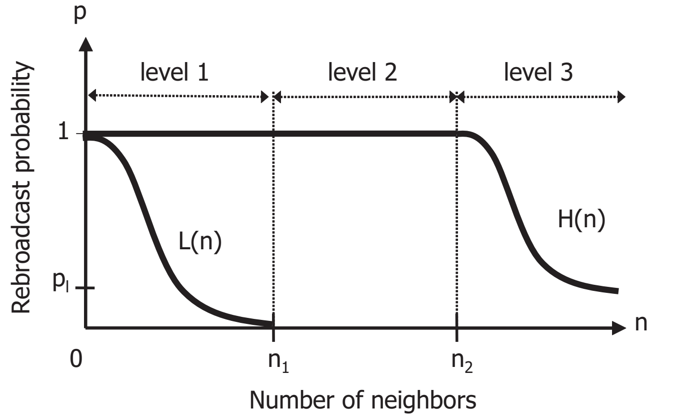

Fig. 1. Abstract shapes of three-level adaptation

This optimization is called SEER-2(n_1, n_2, H(n), L(n)). In section 4.3, we will derive n_1 and n_2 values through experiments.

4 Performance Evaluation

In this section, we first evaluate the performance of our SEER-1(p) scheme and observe the partition ratio of our energy-based diffusion algorithm with different network parameters. Following the experiment results in SEER-1(p) scheme, we derive exact n_1 and n_2 values to set up our SEER-2(n_1, n_2, H(n), L(n)) scheme. We compare our SEER-2 scheme with a simple flooding algorithm and the dynamic probabilistic broadcasting (DPB) algorithm [11]. We implement all the four algorithms and study the following performance metrics, including reachability, saving ratio, the number of message rebroadcasts with different initial energy levels, and extended lifetime.

4.1 Simulation Model

Our simulation is performed in the GloMoSim network simulator [10] (version 2.03). The mobility model used in each of simulations is known as random direction. The transmission range of each node is held constant at 250 meters. The radio frequency at the physical layer is 2.4 GHz of the ISM band. The raw network bandwidth is 2 Mbps and the MAC layer protocol is IEEE 802.11 [3]. One source node is responsible for sending constant bit rate (CBR) flows and each CBR flow consists of 128 byte packets. Our energy consumption model is based on Chen et al. which measured the Lucent 2Mb/s WaveLAN 802.11 cards, observing power consumption cost of 1.4W(transmit), 1.0W(receive), and 0.83W(idle) [1].

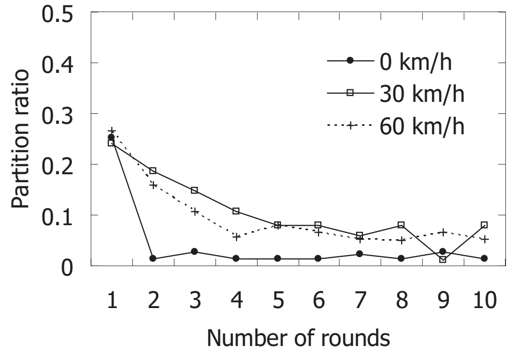

Fig. 2. Partition ratio vs. number of rounds.

4.2 Partition Ratio

Fig. 2 shows the partition ratio vs. the number of diffusion rounds with different node mobility models: 0 km/h, 30 km/h, and 60 km/h. We simulate 200-node networks in a $1500m \times 1500m$ area. Each node has a random initial energy, uniformly distributed over the interval [300 J, 2000 J]. Partition ratio is defined as $\frac{|N_{super} - N_{sub}|}{N}$, where N_{super} and N_{sub} are the number of super-critical nodes and sub-critical nodes respectively after each diffusion round, and N the total number of nodes in the network. We force each node to execute the energy-based diffusion operation once in each round. In Fig. 2, we can see that mobility does not affect our energy-based diffusion algorithm very much. After round 5, the partition ratio is very close to 0, especially for static MANETs. In other words, the ratio between the number of super-critical nodes and the number of sub-critical nodes approaches to the desirable ratio 1:1. This implies that, after few diffusion rounds, half of total nodes can independently classify themselves into the sub-critical group and decrease their rebroadcast probability to save precious residual energy.

4.3 Reachability and Forwarding Ratio

Here we study the performance indicated by the following two metrics, of which the first was studied in [8]:

- *REachability* (*RE*): the number of mobile node receiving the broadcast message divided by the total number of mobile nodes that are reachable, directly or indirectly, from the source node.
- *Forwarding Ratio* (*FR*): The ratio of the nodes that retransmit the packets at least once to the total number of nodes in the network in a broadcast.

We use a fixed area size with different average number of neighbors n. Fig. 3 shows our simulation results for SEER-1(p) with $p = 1$. It can be seen that the results follow the **Observations 1, 2, and 3** discussed earlier. Remember that

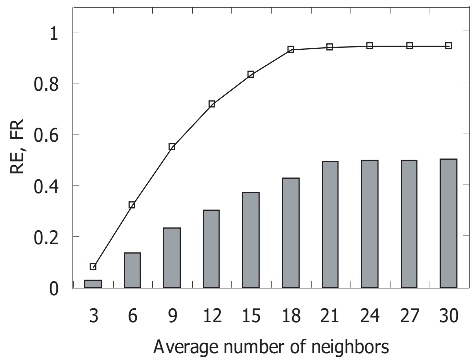

Fig. 3. Performance of SEER-1 scheme: Reachability RE (shown in line) and Forwarding ratio FR (shown in bars) vs. average number of neighbors.

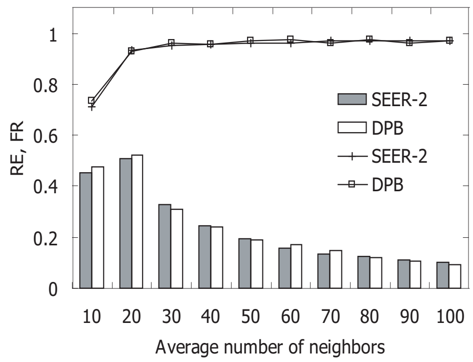

Fig. 4. Performance of SEER-2 and DPB schemes: Reachability RE (lines in upper part) and Forwarding Ratio FR (bars in lower part) vs. average number of neighbors.

sub-critical nodes do not forward messages in this scheme. When $n \leq 15$, a situation that a node has fewer neighbors, RE obviously degrades because some sub-critical nodes are more likely to be located in a critical position to maintain the network connectivity. The fact that sub-critical nodes do not forward messages thus incurs the problem of network partition. When $15 < n < 21$, super-critical nodes suffice to achieve high reachability (RE > 0.83). When $n \geq 21$, the chance of receiving the same messages from other neighbor super-critical nodes raises. We can decrease the rebroadcast probability of super-critical nodes to reduce FR. Intuitively, more redundant transmissions can be saved without sacrificing the reachability. From the results in Fig. 3, we let $n_1 = 15$ and $n_2 = 21$ respectively to evaluate the performance of our SEER-2 scheme. As Fig. 4 shows, RE and FR of SEER-2(15, 21, H(n), L(n)) are as good as those of DPB. This demonstrates that utilizing energy-based knowledge to determine rebroadcast probability can produce satisfying broadcast performance.

4.4 Rebroadcasts

In our experiments, the initial power of nodes is set to be a uniform distribution between 300J and 2000J. In Fig. 5, each diamond symbol along the horizontal axis represents an individual node with initial power of various levels. Fig. 5 shows the relationship between the number of relays and the total 200 nodes of different initial energy. In this experiment, a source node generates a total of 12000 broadcast packets at the packet rate of 20 packets per second. In DPB, the number of relays of each node falls roughly between 5000 to 8000 times. This means that even a node with very low energy still has the same rebroadcast probability as a node with very high energy. As expected, our SEER-2 scheme dramatically divides all nodes into super-critical nodes and sub-critical nodes

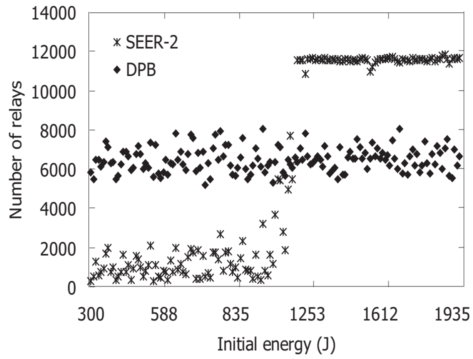

Fig. 5. Number of relays vs. initial energy.

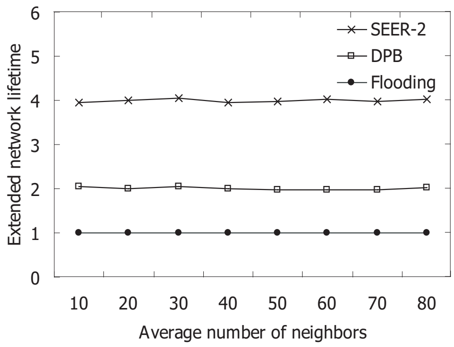

Fig. 6. Extended network lifetime vs. average number of neighbors.

and most rebroadcasting load is shared about evenly by the super-critical nodes. The number of relays of sub-critical nodes is less than 2000 times. It can be noticed that some sub-critical nodes never participate message forwarding. This is because the sub-critical nodes tend to drop the received messages except when the number of its neighbors is less than n_1.

4.5 Network Lifetime

This section shows how much more our SEER-2 scheme can extend network lifetime compared with simple flooding and DPB. We define network lifetime as the time interval from network initialization to the instant of the first node failure due to battery depletion. We assume that the source node has unlimited energy for generating data traffic, and that the remaining 200 nodes start with random initial energy uniformly distributed over the interval [300 J, 2000 J].

Following the results in section 4.3, Fig. 6 shows that the extend network lifetime of SEER-2 scheme is about a factor of 2 and 4 better than DPB and simple flooding respectively for various node density. This is because we concentrate the load of messages forwarding on super-critical nodes. A sub-critical node in this scheme decreases its rebroadcast probability to save energy and can thus extend the system lifetime. Especially in a denser network when the average number of neighbors is greater than the parameter n_2 of SEER-2 scheme, no sub-critical nodes need to participate in rebroadcast.

5 Conclusion

In this paper, we present two energy-efficient relay schemes namely SEER-1 and SEER-2 respectively. Both schemes utilize a localized energy-based diffusion algorithm to estimate a system energy approximation (SEA), with which each node can independently determine an appropriate rebroadcast probability. To optimize the energy efficiency, and to extend network lifetime without sacrificing the reachability, we also study how to dynamically adjust the rebroadcast probability by using neighbor connectivity information. Simulation results show that the reachability and forwarding ratio of our SEER-2 scheme are as good as those of DPB. This demonstrates that utilizing energy-based knowledge to determine rebroadcast probability can efficiently reduce redundant transmissions without sacrificing reachability. Besides, our SEER-2 scheme dramatically concentrates the greater part of message forwarding load on the nodes with higher residual energy. Following the results, extended network lifetime of SEER-2 is about a factor of 2 and 4 better than that of DPB and flooding scheme respectively. We expect this performance improvement to become even more significant in denser networks. In the future work, we plan to apply these schemes to current MANETs protocols, such as multicast or routing protocols.

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