Mitigating the Flooding Waves Problem in Energy-Efficient Routing for MANETs [*]

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Abstract

In wireless mobile adhoc networks (MANETs) channel and energy capacities are scarce resources, a lot of energy-efficient routing protocols for MANETs have been previously proposed to take into consideration the nodes' residual energies when establishing routes between source-destination pairs.

In this paper we are not trying to introduce a new routing algorithm to be added to the already proposed stack of energy-efficient protocols, but rather, we identify a problem in cost-based energy-efficient routing for MANETs, we call this problem "Flooding Waves". We show that the "Flooding Waves" is a serious problem in dense networks, to the extent that the excessive energy overhead consumed in these waves can outweigh the gain achieved by energy-efficient path selection. We propose the "Delayed-Forwarding" as a solution for this problem. We provide both a simulation analysis and a simple theoretical framework to validate and support this solution.

1 Introduction

Adhoc networking is expected to have a significant impact on the efficiency of many military and civilian applications, such as, combat field surveillance, disaster management, data gathering, monitoring and sensor networks. One of the constraints for building an efficient adhoc network is *finite* battery capacity. Since the network nodes are battery operated, and in many cases they are installed in an environment where it may be hard (or undesirable) to retrieve the nodes in order to change or recharge the batteries, the network nodes need to be energy conserving so that the battery life and hence the network lifetime are maximized. As a result, a lot of the research efforts, as cited in Section 2, have been directed toward proposing new energy-efficient routing protocols that aim at extending the network's lifetime.

In this work, we are not trying to introduce a new routing algorithm to be added to the already proposed stack of energy-efficient protocols. Rather, we are interested in a more fundamental question about the design of energy-efficient routing to maximize the useful lifetime of an adhoc network. Our contribution is identifying and solving a problem in cost-based energy-efficient routing for MANETs, we call this problem *"Flooding-Waves"*. To the best of our knowledge, no prior work discussed this problem or tried to solve it.

As discussed in details later, *Flooding-Waves* problem stems from the same root as the *Broadcast-Storm* problem [14, 21] faced in conventional power-oblivious MANET routing protocols. However, the *Flooding-Waves* is more profound because it is a series of flooding storms instead of just one storm. We show that this is a serious problem in dense networks, to the extent that the excessive energy overhead consumed in these waves can outweigh the gain achieved by energy-efficient routing.

It has been previously shown that the *Broadcast-Storm* problem can be solved by probabilistic forwarding schemes [12, 17, 20, 22], that is, in order to flood, a relay node broadcasts a message with probability p and takes no action with probability $1-p$. However, it is unclear how a similar approach can be applied in cost-based energy efficient routing. In this case, and as explained later, the destination node is interested in collecting the route-request (RREQ) messages from **ALL** the relaying nodes in order to be able to select the most energy-efficient path from all the available routes. Probabilistically forcing nodes to refrain from forwarding the RREQ message prunes the available routes set and can end-up with choosing an energy-consuming path. In this paper, we propose the *"Delayed-Forwarding"* as a solu-

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tion for the flooding-waves problem. We provide both a simulation analysis and a simple theoretical framework to validate and support this solution. Our results show that when the *Delayed-Forwarding* is applied, the total number of received packets (the useful work done by the network) increases by almost 46% for dense networks.

The rest of the paper is organized as follows: Section 2 presents related work. Section 3 explains the operation of energy-efficient cost-based routing. Section 4 describes the flooding waves problem and proposes a solution for it. We conclude the paper in Section 5.

2 Related Work

We can classify the previous research on energy-efficient routing into the following categories:

Clustering Routing Protocols organize the network into clusters, and for each cluster a coordinator node is elected that performs the base station functions, as proposed in [3] and [15]. Furthermore, because the coordinator's role consumes the resources of certain nodes, a group of schemes were proposed in which coordinators are rotated among network nodes (e.g., [1,7,8,23]). Energy savings reported for this category of protocols is very promising. However, we think that it is more suited to sensor networks for two reasons: First, the mobility rate of sensor nodes is not as high as mobile adhoc nodes and hence, the re-clustering overhead is not significant. Second, the traffic pattern of a sensor networks is typically an on demand event-driven traffic, and hence, most of the time the nodes' wireless component can be completely turned off. Moreover, clustering protocols assume complete time synchronization and complete knowledge of neighboring nodes, these conditions are too hard to achieve without the existence of a centralized control station.

Minimum Transmission Energy Routing Protocols came about because the maximum power is consumed during the transmission mode. much research has been proposed to minimize the transmission power and thus maximize the network lifetime. For example, [5, 11] send the data to the nearest neighbor in a multihop fashion until reaching the destination. Other protocols control the transmission power not only based on the distance between the sender and the receiver but also based on different channel conditions. For example, the scheme presented in [16] adjusts the transmission power according to the SNR at the receiver. Analogously, the protocol in [4] chooses an appropriate transmission power based on the packet size. The main disadvantage of these protocols is that they depletes the energy of the nodes along the most heavily used routes.

Cost-Based Routing Protocols use a cost function to select a route from the set of the available routes. Conventional MANET routing protocols, being concerned with end-to-end delay, tried to minimize the cost (number of hops) of a route between a source and a destination. Similarly, cost functions have been extensively used to provide energy-efficient routing. Singh [19] was the first to propose using several power-aware metrics in route selection. Recently, a lot of research (e.g., [6,13]) has proposed cost functions that take into consideration the nodes' energy levels in order to bypass energy-poor nodes in routing. As mentioned before our contribution is not to present a new protocol to be added to this category of cost-based routing but rather to present some guidelines on how to effectively apply such protocols.

3 Cost-Based Energy-Efficient Routing

In a *cost-based* routing protocol, each node adds its current cost to the received RREQ and rebroadcasts it. Upon receiving the first request, the destination sets a timer. During a specified interval, the destination collects all incoming requests. When the timer expires, the destination selects the best route and includes it in the generated route reply. There is a tradeoff in determining this timeout value: it should be long enough to collect all the route requests and at the same time it shouldn't increase the overall end-to-end delay or cause the source to timeout and send a new request. In our implementation, the value of the timeout is set to be proportional to travel time of the first route request received. This is done to factor in the distance between the source and the destination. The energy-efficient cost-based network designer should answer two questions: (1) How to assign a cost for a wireless link and (2) how to aggregate the cost of a complete route from the source to the destination. In this section, we briefly describe each design choice.

3.1 Wireless Link Cost Function

The cost function assigned to a wireless link should be designed to satisfy an important metric, namely an **efficient fair** utilization of the available nodes' energies. A wireless link cost function can take the following form [2,13,18]:

$$Cost_{node_i} = (E_{Tx_i} + E_{Rx})^{\alpha} \cdot \left(\frac{\theta_{F_i}}{\theta_{R_i}}\right)^{\beta} \qquad (1)$$

where: E_{Tx_i} is the energy consumed during transmitting a packet from $node_i$ to $node_{i+1}$. E_{Rx} is the energy consumed during receiving a packet. θ_{F_i} and θ_{R_i} are the full energy and current remaining energy of $node_i$, respectively. α and β are positive weighing factors.

When the wireless link cost given by Equation (1) increases, the probability for selecting this link to be included in the route between the source-destination pair decreases. As a result, the node willingness to participate in routing and relaying other nodes' data is inversely proportional to the link cost. The route used is selected to favor minimum total energy consumption and bypass energy-poor nodes.

3.2 Cost Aggregation and Balanced Energy Concept

As described in Section 3.1, each node adds its current cost (see Equation (1)) to the received *Route Request* and rebroadcasts it. The destination then selects the optimal route from all the *Route Requests* it received and includes it in the generated route reply. Usually, the destination sums up the costs of individual links to evaluate the aggregate route cost. The destination node picks the route that has the minimum cost summation as the route to be used for this flow.

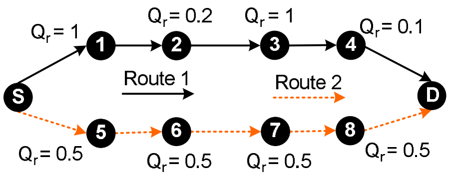


Figure 1. Aggregate Energy Capacity per Route, (Q_r = Relative Remaining Energy)

However, it should be mentioned that, this implementation doesn't take into consideration the energy variance of nodes along the path. Energy-poor nodes can be penalized because they have high-energy neighbors. This problem is illustrated in Figure 1, where Route 1 ($sum = 2.3$) is favored over Route 2 ($sum = 2.0$), causing energy-poor nodes (Node 2 and Node 4) to be rapidly depleted from their energy.

To further illustrate this problem, Figure 2 shows the arithmetic, geometric and the harmonic means of two numbers X and $(100 - X)$, where X ranges from 0 to 100. As shown in figure, the arithmetic mean (which is directly related to the summation of values) is constant (50) for all values of X. The value of the arithmetic mean of 0 and 100 is the same as the arithmetic mean of 50 and 50. On the other hand, the geometric and the harmonic mean are both more discriminating than the arithmetic mean, that is, they are more sensitive to the variance between the two numbers. They reach their maximum when the two numbers are 50 (variance =0) and reaches 0 when one of the numbers is 0 (maximum variance).

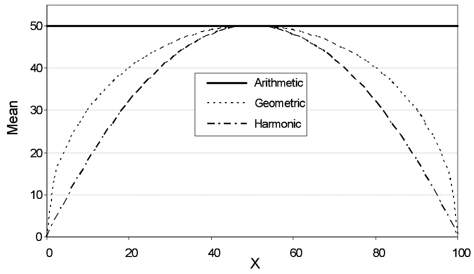


Figure 2. Arithmetic, Geometric and Harmonic Mean of X and $(100 - X)$

As described in Section 3.3, we compare the performance of two energy-efficient routing protocols, the first uses summation to aggregate the route cost, while the second uses multiplication (which is directly related to the geometric mean) as the aggregation function for the route cost. We believe that, when two routes have the same number of hops, multiplication of individual link costs will yield a better energy-balanced route. It should be clear that, the node's cost is designed to be ≥ 1 and hence, the aggregated cost function is a non-negative monotonically increasing function. In our future work, we plan to investigate thoroughly the balanced energy problem (which is orthogonal to the flooding-waves problem we are trying to solve in this paper) and devise a better algorithm to take care of the energy variance along the route.

3.3 Simulation Analysis for Small Networks

To evaluate the performance of cost-based energy-efficient routing in small networks, we used the *Network Simulator* (NS2) to simulate a 40-node network. The nodes are randomly distributed in an area of $1000 \times 1000\ m^2$. A total number of 40 flows are generated, each flow is assumed to be a constant bit rate (CBR) flow. Each flow has the rate of 2 packets/source/sec and the packet size is 512 bytes. The sources and destinations of the flows are randomly picked from the network nodes.

Initially, all the nodes are assumed to have full battery level of 5 joules; battery capacity was set to a small value to scale down the simulation time. The total simulation time is 1600 seconds, the flow sources start transmitting at a time randomly chosen between 0 and 400 seconds and stops transmitting at a time that is uniformly distributed between the flow start time and the simulation end time. Simulation parameters are summarized in Table 1.

Table 1. Simulation Parameters

Parameter	Value
Number of Simulation runs	10
Network Size	$1000 \times 1000\ m^2$
Node range	250 m
Node initial energy	5.0 J
Number of connections	40
Packet Size	512 bytes
Transmission rate per source	2 pkts/sec

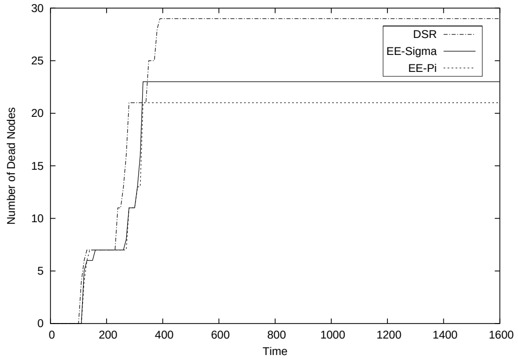
In our analysis we compare three protocols (1) conventional **DSR** [9, 10], (2) **EE-Sigma** and (3) **EE-Pi**. The last two are energy-efficient routing protocols that use addition and multiplication to aggregate the total route cost, respectively. The following metrics are used to evaluate the performance of the different protocols:

- *Number of dead nodes*: A dead node is defined as a sender node whose energy level is below that needed to transmit one packet or a receiver node whose energy is less than that required to receive a single packet. The number of dead nodes reflects the network lifetime.
- *Number of received packets* denotes the number of correctly received data frames that successfully arrived at their final destination.

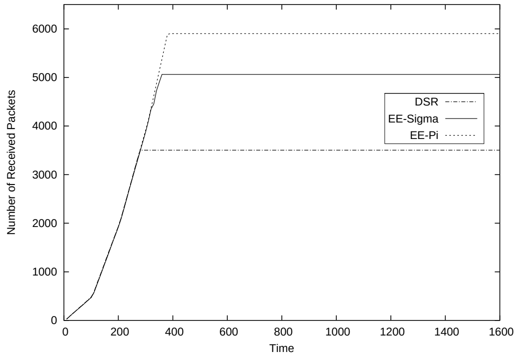
Figure 3 presents the simulation results for the small network of 40 nodes. Figure 3(a) compares the accumulated number of dead nodes over time and Figure 3(b) shows the cumulative number of the correctly received data packets versus time. As expected, DSR consumes the available nodes energy at a high rate and hence, it has the highest number of dead nodes and the lowest number of received packets.

Energy-efficient routing tries to bypass energy-poor nodes and at the same time pick a route that will consume less energy. Therefore, it extends the network lifetime and hence, more work (received packets) can be accomplished by the network. Toward the end of the simulation, the curve in Figure 3(a) flattens because most of the network nodes are dead and the source-destination pairs are disconnected.

The network throughput is defined as the total number of received packet divided by the time. The throughput can be seen as the slope of the curve shown in Figure 3(b). It is important to indicate that the throughput for energy-efficient routing is almost the same as that offered by DSR. As a result, the destination dynamic timeout value we used has an insignificant effect on the throughput. Toward the end of the simulation the curve in Figure 3(b) flattens which indicates that the throughput of the network is close to zero and no more messages are being received. This is because most of the network nodes are dead and no data packets can reach their destinations. As shown in Figure 3(b) EE-sigma increased the number of received packets by 44% while EE-Pi boosted up the number of received packets by 68%.



(a) Cumulative Number of Dead Nodes



(b) Cumulative Number of Received Packets

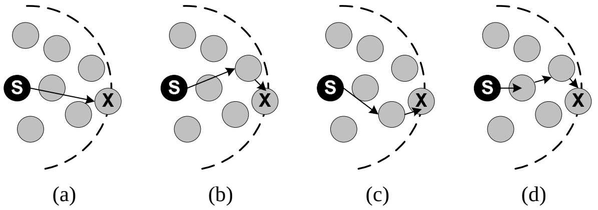
Figure 3. Simulation Results for 40-nodes

4 Flooding Waves in Cost-Based Energy-Efficient Routing

4.1 Problem Definition

The simulation results presented in Section 3.3 show a significant improvement in the performance of the energy-efficient routing over conventional energy-oblivious routing protocols. However, it should be noted that, these results are only valid when we have a low-density network. When the node density increases a problem arises and the performance of the network is severely degraded. In this section we are going to discuss the origin of this problem, which we call the *"Flooding Waves"* problem. To the best of our knowledge, no prior work discussed this problem or tried to solve it for an adhoc network.

Figure 4 shows the neighborhood of the source in a high-density network. For simplicity, assume that all the network nodes have the same energy. Hence, the transmission distance (energy consumption) is the only factor that determines the efficiency of a route. Moreover, assume that the time is slotted with slot time τ, where τ is long enough for the contention between the transmitting nodes in one neighborhood to be resolved.



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

Figure 4. Flooding Waves Problem

When a source node *S* needs to transmit a packet and it doesn't know the route to the destination, it sends out a route request. All the nodes in the transmission range of the source receive this request after time τ. In this case there is a difference in the behavior of the conventional DSR and that of an energy-efficient routing, as described next.

In DSR, at time τ, Node *X* receives the request transmitted by the source (as shown in Figure 4(a)) and it rebroadcasts the request to its neighborhood. Later, as shown in Figures[4(b)-4(d)], Node *X* will receive copies of the same request, however, it drops all these packets as they are redundant copies of a request it has already handled.

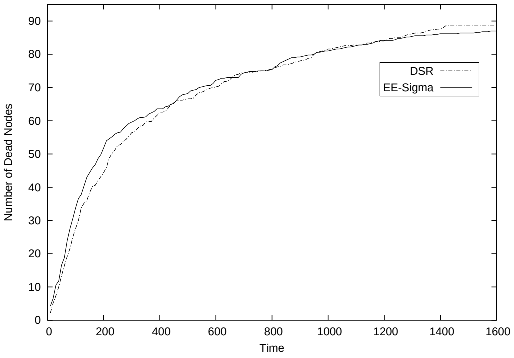
In energy-efficient routing (e.g. [19], [6], and [13]), similar to DSR, Node *X* rebroadcasts the first request it gets after τ to its neighborhood. At time 2τ, and as shown in Figure 4(b), X receives another copy of the request. However, X doesn't discard the received packet. It first checks the cost of the new request received, if the new cost is less than the one already transmitted, the request is rebroadcast, otherwise, it is discarded. Since there is a non-linear relation between the transmission power and the transmission distance the cost of the request received at 2τ will probably be less than that received at τ and hence, it will be rebroadcast. Similarly, in subsequent time slots, as shown in Figures [4(c)-4(d)], Node *X* will receive copies of the request, and each one of those will have a lower cost than the one already transmitted. As a result, X will rebroadcast all the received route requests.

It should be noted that, each request transmitted out of Node *X* completely floods the network (*Broadcast-Storm* [14, 21]) until it reaches the destination. Moreover, the same behavior is repeated at each hop along the route (not only the source's neighborhood). As a result, these *waves* of requests represent a huge route discovery overhead and this overhead increases with the increase of the node-density. The wasted energy consumed in transmitting these flooding waves diminishes the energy gain resulted from using an efficient route. To further illustrate this problem, we used NS2 to simulate a similar network setup to that described in Section 3.3 (see Table 1). However, the number of nodes is increased from 40 to 150 to increase the network density.

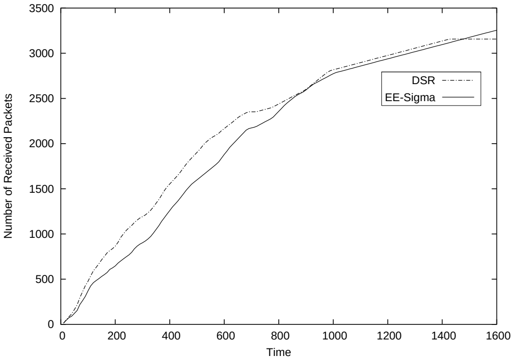
Figure 5 presents the simulation results for a dense network of 150 nodes. Figure 5(a) compares the accumulated number of dead nodes over time and Figure 5(b) shows the cumulative number of the correctly received data packets versus time. As shown in Figure 5(a), the number of dead nodes when using DSR is almost the same as that when using an energy efficient routing algorithm. This surprising result is because the forwarding nodes waste a lot of energy in the route discovery overhead for each new route discovered. Figure 5(b) represents another result that seems, at first, surprising: For high node-density networks, DSR is actually delivering almost the same total number of packets to their final destinations as that delivered when using EE-sigma. As shown in the figure, the energy gain achieved by energy-efficient routing is canceled out by the huge overhead the nodes are paying to discover these routes. The overhead is energy wasted in rebroadcasting the requests in addition to time and buffer capacity wasted due to the increased contention among nodes and also a degraded network throughput (slope of curve).

4.2 Delayed Forwarding

As described in Section 4.1, the *"Flooding Waves"* problem wastes a lot of energy from the intermediate relay node and severely degrades the network performance. As a result, a mitigation scheme for this problem has to be devised.



(a) Cumulative Number of Dead Nodes



(b) Cumulative Number of Received Packets

Figure 5. Simulation Results for 150-nodes

Reconsidering the example in Figure 4, it is clear that, in order to solve this problem, Node X has to delay for a certain period before rebroadcasting the best available request it received. With similar reasoning, it is apparent that each node in the network has to apply its own delay before forwarding the route request in order to suppress the redundant packets. We call this mitigation scheme *"Delayed Forwarding"*.

However, it should be noted that, determining the timeout value to be applied at each relay node is not a simple question to be answered. Intuitively, a *fixed* timeout value (δ) for all the nodes will not do any good, because it will just increase the end-to-end delay without decreasing the number of forwarded requests. For illustration, reconsider the example shown in Figure 4. It is apparent that, Node X receives the RREQ from the source at τ and forward it. It receives the request indicated in Figure 4(b) at $\tau + \delta$ and forwards it. Similarly for the requests shown in Figure 4(c) and Figure 4(d) which occur at $2 \cdot (\tau + \delta)$ and $3 \cdot (\tau + \delta)$, respectively.

On the other hand, waiting for a *random* timeout before rebroadcasting the request, will not be enough to suppress a significant number of the redundant packets. The reason for such claim is illustrated in Figure 6.

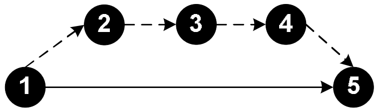


Figure 6. Random Forwarding Delay at Each Relay Node

In the example shown in Figure 6, each node waits for a timeout uniformly distributed in the range of [0..X] before forwarding the route request. As a result, the probability that Node 5 receives the request directly transmitted by Node 1 (worst cost) before the timeout expires is 1. On the other hand, the probability that Node 5 receives the least cost request before the timeout expires decreases with the increase of number of hops between the Node 1 and Node 5. Consequently, the probability that a random forwarding delay will suppress redundant packets decreases with the increase in the node density.

Examining the example shown in Figure 6, it is clear that for Node 5 to suppress all the redundant requests it has to wait longer than, for instance, Node 2. Accordingly, we propose that a relay node i receiving a request from another node j delays for a timeout value which is proportional to the distance between the node i and node j. We next present a simple analytical model for a linear network to validate this assumption.

4.3 Analytical Model for a Linear Network

In our network model, we assume that nodes are equidistant and that the energy required to transmit a packet between any two adjacent nodes is E_{Tx}, while that required to receive a packet is E_{Rx}. The number of nodes within one transmission range of a node is assumed to be n. The minimum number of hops from the source to the destination is assumed to be H:

$$H = \frac{\textit{Path Length}}{\textit{Node's Transmission Range}} \qquad (2)$$

Similar to Section 4.1, we assume that all the network nodes have the same residual energy. Hence, the energy consumption ($E_{Tx} + E_{Rx}$) is the only factor that determines the efficiency of a route. Finally, we assume that the time is slotted with slot time τ, where τ is long enough for the contention among transmitting nodes to be resolved. First, we compare the routing overhead for the conventional DSR with that of an energy-efficient routing scheme that does not use a forwarding delay. Then we derive the optimal forwarding delay that each node should wait before rebroadcasting the received request.

In DSR, each relay node broadcasts the request once, regardless of its cost, and discards all redundant copies of the same request. Intuitively, the number of requests transmitted (overhead) is just the total number of nodes in the network and is given by:

$$Overhead_{DSR} = n \cdot H \tag{3}$$

In energy-efficient routing, the relay nodes do not drop duplicate requests but forward the duplicate if it has a lower cost. Figure 7 shows a simple example for a linear network where the node's transmission range includes two other nodes (a total of 3 nodes per neighborhood). In the figure, time flows from top to bottom where each row represents a new time slot. Dark nodes are those forwarding the requests. For example, the dark node in the 2nd row, 3rd column means that Node 3 forward the RREQ received from S. Analogously, dark node in 3rd row, 3rd column sends the RREQ received from Node 2.

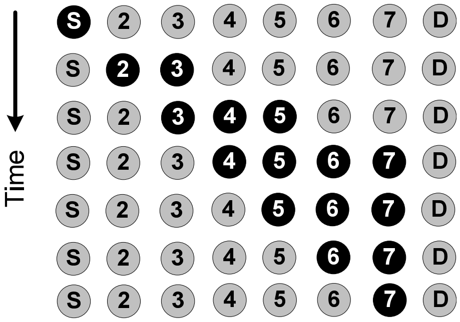


Figure 7. Route Request Overhead

The reader might think that since the number of transmitting nodes in 4th row is larger than that of the 3rd row, then the time needed for transmission (τ) should be different for each row. However, it should be kept in mind that transmissions from different neighborhoods can occur concurrently: As a result, τ is fixed and is equal to the time needed for the nodes in *one* neighborhood ($2 \cdot n$ nodes because of hidden terminals) to resolve their contention. In the example given in Figure 7, τ is assumed to be long enough for 6 nodes to resolve contention.

As shown in Figure 7, at $\tau = 0$, S broadcasts a route request which is received by 2 and 3. At $\tau = 1$, both 2 and 3 forward the request. When 2 transmits 3 and 4 receive. Similarly, 4 and 5 receives from 3. At $\tau = 2$, 3 transmits because the request received from 2 has a lower cost than that received from S. As shown in figure, the number of nodes transmitting grows (by $n-1$) until the edge of the expanding wave reaches the destination (at $\tau = H$), and then, it decreases by one for each subsequent time slot. The overhead is the number of requests transmitted, which is equivalent to the number of dark nodes. As a result, for a general linear network, it is easy to prove that the overhead of routing in energy-efficient network is:

$$\begin{aligned} Overhead_{EE} &= \left((n-1) \cdot \sum_{i=1}^{H} i\right) + \left(\sum_{i=1}^{(n-1)\cdot H} i\right) \\ &= \frac{H \cdot (n-1) \cdot (n \cdot H - 2)}{2} \end{aligned} \tag{4}$$

where the first term represents the number of growing nodes until the destination is reached and the second term represents the number of decreasing transmitters after that.

Comparing Equation (3) and Equation (4) illustrates the huge overhead imposed by an typical energy-efficient routing scheme. We propose using the *"Delayed Forwarding"* mechanism to reduce this effect. Optimally, the routing overhead in an energy efficient protocol is equal to that of the DSR, where each node forward the request only once. Next we derive the optimal delay for the linear network.

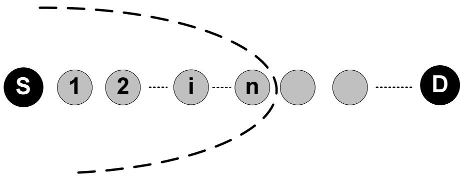


Figure 8. A Linear Adhoc Network

Consider the linear network shown in Figure 8. After one slot time, Node i (i hops away from source) receives a request from the source. The cost of this request is $E_{Tx} \cdot i^2$. After two time slots, Node i receives $n-1$ requests. The best cost request from those received is the one that is forwarded form a node at exactly mid distance between the source and Node i. The cost of this request is $E_{Tx} \cdot (i^2/2) + E_{Rx}$. With similar reasoning, after d time slots the best received request has a cost of:

$$Cost = E_{Tx} \cdot \frac{i^2}{d} + (d-1) \cdot E_{Rx} \qquad (5)$$

For Node i to suppress all redundant requests, it has to wait d time slots, such that the cost of the request received at $d+1$ is greater than or equal that received at d. This is shown in Equation (6)

$$(E_{Tx} \cdot \frac{i^2}{d} + (d-1) \cdot E_{Rx}) \geq (E_{Tx} \cdot \frac{i^2}{d+1} + (d) \cdot E_{Rx}) \quad (6)$$

Solving the inequality given by Equation (6), we can deduce that each relay node has to wait for:

$$Delay_{node_i} \propto \sqrt{\frac{E_{Tx_i}}{E_{Rx}}} \qquad (7)$$

where $Delay_{node_i}$ is the timeout value to be applied at node i and E_{Tx_i} is the transmission energy required to reach node i from the previous forwarding node. As a result, the optimal timeout value at node i is proportional (at least for the linear network) to the the distance between this node and the previous forwarding node.

4.4 Simulation Analysis for Delayed-Forwarding

To evaluate the performance of the adhoc network when the proposed delayed forwarding is used we used NS2 to re-simulate the same network setup as that described in Section 4.1. In our analysis we compare four protocols (1) conventional **DSR**, (2) energy-efficient routing that does not use "delayed forwarding", as describe in Section 4.1, **EE-Sigma**, (3) energy-efficient routing that use delayed forwarding and addition to aggregate the total route cost, **EE-Sigma-Delay**, and (4) energy-efficient routing that use multiplication as the cost aggregation function and use delayed forwarding at intermediate relay nodes, **EE-Pi-Delay**.

Figure 9 shows the number of route requests forwarded at intermediate relay nodes versus time. The number of requests forwarded when no delay is applied (EE-Sigma) is significantly larger than that forwarded when using DSR. The relay node's energy is not used to deliver data packets to their destinations but rather it is wasted in forwarding these overhead packets. When the delayed forwarding (EE-Pi-Delay) is applied, the number of requests forwarded in energy-efficient routing is almost as low as that forwarded when using DSR and hence, the energy overhead is minimized. For visual clarity, we omit the curve for EE-Sigma-Delay as it is very close to that of EE-Pi-Delay.

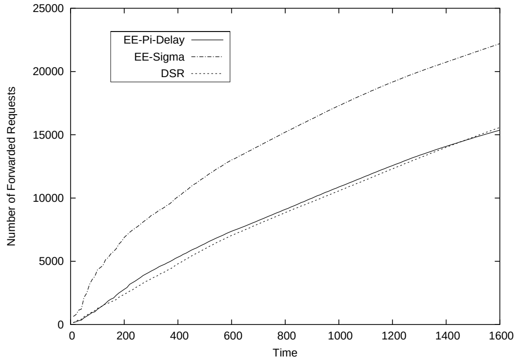


Figure 9. Cumulative No. of RREQ Forwarded at Relay Nodes versus Time; Total Nodes = 150

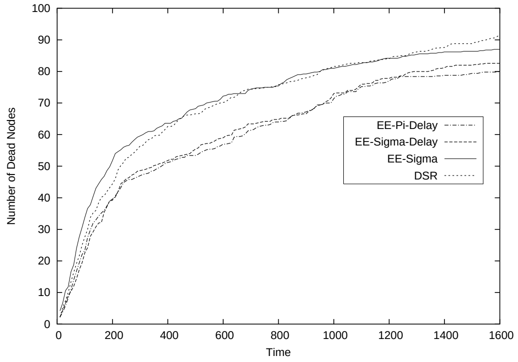


Figure 10. Cumulative No. of Dead Nodes versus Time; Total Nodes = 150

Figure 10 compares the accumulated number of dead nodes over time. As shown in figure, and similar to the result shown in Figure 5(a), the performance of EE-Sigma is severely degraded due to the wasted overhead and therefore, the number of dead nodes is slightly more than that when using DSR. However, when our suggested forwarding delay (EE-Sigma-Delay and EE-Pi-Delay) is used, the route discovery overhead is minimized and therefore, the energy savings from using an efficient route decreased the total number of dead nodes in the network. As shown in Figure 10, the energy-efficient routing that uses delayed forwarding decreased the number of dead nodes by 19% over the DSR.

Figure 11 shows the cumulative number of the correctly received data packets versus time. Figure 11 shows a similar trend of results as that shown in Figure 10. When no forwarding delay is applied the performance of EE-Sigma is as bad as that of the DSR. However, when a forwarding delay is applied a signifi-

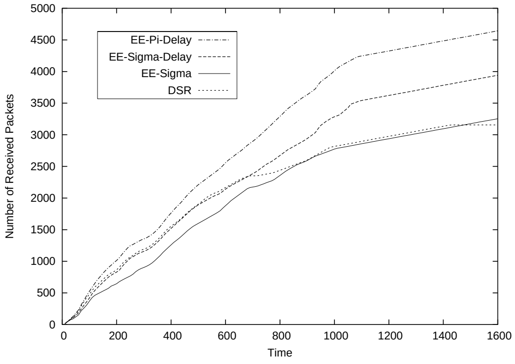


Figure 11. Cumulative No. of Received Packets versus Time; Total Nodes = 150

cant performance improvement can be seen. EE-Sigma-Delay increased the number of received packets by 22% over the DSR. While EE-Pi-Delay boosted the number of received packets by 46% over DSR.

5 Conclusion

In this paper we introduced some guidelines to be applied to the family of cost-based energy-efficient routing protocols. we identified the problem of *"Flooding Waves"*, which is a common problem in any cost-based routing scheme. We introduced a simple analytical model for a linear network to illustrate this problem and we proposed the forwarding delay as a solution.

Through simulation analysis we showed that the forwarding delay boosts the performance of energy-efficient cost-based routing protocol. We showed that the total number of received packets for a given energy budget increases by 46% for high-density networks.

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