Energy-Aware Post Settings:

A Study on Performance Gain by Adding Relaying Nodes in Wireless Ad-hoc Networks

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Abstract— We explore the effect of certain network properties for energy balancing in wireless ad-hoc networks. We report the extent to which the improvement on energy balancing can be achieved by strategic placements of an additional relaying node in networks running energy-efficient routing protocols.

Keywords: *energy balancing, relaying node placement, wireless ad hoc networks.*

I. INTRODUCTION AND RELATED WORK

Routing protocols considering the maximization of operational lifetime are of importance due to the nature of limited power supply in wireless ad hoc networks. The importance has resulted in a tremendous number of newly proposed routing protocols to achieve energy-efficiency. Some of the protocols have delicate conditions for being easily used in practice. Instead of developing new protocols, we take a different approach. We observe that by simply adding a node to a deployed network, we might be able to achieve an improvement of energy-efficiency.

The meaning of operational lifetime of a network may be different, depending on the objective of a targeted network scenario. The problem of a node's failure, which may result in network partitioning, is critical in ad-hoc networks while the problem is unimportant in sensor networks. Ad-hoc networks incline towards personal communication, and every member has to be connected with other members in many cases. In this paper, for the definition of network lifetime, we follow a node's death, the first node's death due to its energy exhaustion. The first node is called the *critical* node. Our first goal is to study generally beneficial network properties, not specific to a certain networks, and to identify the best positions to set a single relaying node so as to maximize the operational lifetime. Consider the scenario of firefighting or disaster recovery events. To prolong the lifetime of a network, only a member can be added to the existing network. More precisely, we attempt to provide methods that attack the problem of high traffic regions by placing relaying nodes in the regions in which high congestion is detected.

Recent studies that use relaying nodes are mainly for the purpose of solving maximal area coverage problems [1][5][6], or providing fault-tolerant sensor networks [2][3][7]. Based on the network structure, recent research of relaying node placements can be grouped by placements for single-tiered or two-tiered networks [3]. In single-tiered relaying node placements, a sensing node forwards packets for its any

neighbors. On the other hand, in two-tiered relaying node placements a sensing node does not forward packets for its neighbors and transmits its data either to relaying nodes or data sink nodes. For the purpose of optimizing operational lifetime of two-tiered networks, in [5] the authors study the positions of optimal relaying stations and use linear programming to solve this relay allocation problem. In [6] the authors study hierarchical mobile backbone networks and use relaying nodes for maintaining connectivity of nodes. They transform the problem to the connected geometric disk cover problems and then solve the sub-problems. For the purpose of maintaining fault tolerant sensor networks, in [7] the authors present the algorithms to establish, given a desired connectivity parameter k , k disjoint paths between every pair of nodes by placing additional relaying nodes. Most studies in this research domain propose the algorithms of choosing a small number of relaying nodes for ensuring or improving the connectivity between nodes or between sensing nodes and the base station. The problem of finding optimal places for relaying nodes is not trivial; in [4] the authors proved the NP-hardness of this problem. Due to the complexity, many proposed studies in this research area are to provide the approximation algorithms [3] [6] [7].

We consider the problem of energy balancing or lifetime extension with a single extraneous node in a single-tiered ad-hoc network structure. The goal of this paper is to provide placement methods of a relaying node, which should be simple to use, to react to a crowded region and to reroute the traffic of that region. In other words, we study the problem of how to maximally further improve the network lifetime that is achieved by energy-efficient routing protocols, by adding only a single additional relaying node in a existing network. To enable this, we first explore beneficial properties of wireless ad-hoc networks. Then we choose the most appropriate position and set a single relaying node at the position. In fact, the methods we propose are independent of the underlying energy-efficient routing protocols and can be applied to any. In this paper we evaluate the performance of the methods over our previously proposed energy-balancing protocols [8], which are a centralized routing protocol, referred to as C-Limax, and a localized routing protocol, referred to as L-Limax, for the purpose of optimizing network lifetime. In the centralized routing protocol we assume global knowledge of the network and find the optimal routes between any source and destination node at the global vantage point for the purpose of energy balancing. As a result, the global knowledge results in near optimal solutions. In the localized routing protocol each node

depends on its local information of one-hop neighbors for achieving the same objective. The properties and the results from these localized and centralized protocols can be used as a guide for future relaying node deployments for the purpose of energy balancing.

II. PROBLEM STATEMENTS

A. Network Model and Assumptions

We consider wireless static ad-hoc networks comprising homogeneous nodes in a two-dimensional plane, and each node is initially equipped with a same amount of energy. The network is shown as a directed graph, where the nodes of the network correspond to the set of vertices and the communication links corresponds to the set of edges. The reason why directed graphs are used is because the links of both forward and backward communication costs are asymmetric in low power wireless networks [9]. The link qualities are based on the cumulative density function [9]. The communication pattern to be used is peer-to-peer, which is a traditional wireless personal communication pattern. In the peer-to-peer communication we consider, each node sends a same sized packet to every other node in a round robin fashion. In this communication we assume an interference-free MAC protocol without simultaneous transmission because many long-term monitoring applications may operate at low rates. In this study a wireless node's radio is in one of the following three states: transmission (referred to as Tx), receiving (referred to as Rx), and idle/listening. We use the energy measurements in [10]. The numbers of the power consumption are set to 1.9W for Tx, set to 1.5W for Rx, and set to 0.75W for listening. We also assume that the location information of nodes is available. Lastly, nodes in a network with a certain density are randomly distributed, and the density is defined as the number of nodes per square meter.

B. Relay Nodes

A relaying node has the same standard features with the already deployed nodes, whose goal is to create alternative paths avoiding the burden of energy-weak nodes. Not to simplify the problem, but to enable us to carefully examine our proposed methods, we analyze the performance gain by a single relay node; without considering per node cost, multiple relaying nodes are more beneficial in terms of overall performance improvement, though. In fact, deploying multiple relaying nodes iteratively up to the available number is not a clever way because there are often cases where better placements can be found; this is our on-going research.

C. Metrics

We define **improvement** to evaluate the performance gain from our methods. Let E_{After} be the dissipated energy by the critical node after deploying a relaying node to the original network and E_{Before} be the dissipated energy by the critical node before adding a node. Then, the improvement due to adding a node is defined as $(E_{\text{Before}} - E_{\text{After}}) / E_{\text{Before}}$.

When a new technique is developed, one important question is how much improvement is satisfactory. The higher

improvement, the better; but to decide whether the proposed technique is acceptable or useful in terms of performance gain, we need to determine the satisfactory extent of improvement. We call this extent **threshold**, and the threshold value is, reasonably, defined as the number of added nodes divided by the number of nodes originally deployed. We argue that the proposed method is acceptable if the amount of improvement is equal to or greater than this threshold value. In our case, because only a node will be added, the threshold becomes one divided by the number of nodes in the original network.

D. Problem Formulation

We formally state our problem as follows.

Given a set of deployed wireless nodes, can we reduce the dissipated energy of the critical node of a network more than a given threshold value by positioning a single relaying node to the network?

III. METHODS OF ONE RELAYING NODE ADDITION

To achieve satisfactory energy balancing in a network, which is required for extending operational lifetime, placing an extraneous node is simple but can be effective for many applications. We present the methods that suggest the candidate locations for an extraneous node and report the extent of improvement. We start by introducing the network properties considered importantly.

A. Investigation of Beneficial Properties

The hardest part associated with the task of adding nodes is the identification of regions, in which the extraneous node helps the critical node's relaying task so that the critical node is alleviated in terms of its energy dissipation.

The first method is to use the information of nodes' energy expenditure in the previous phase. It is a natural but effective method. The critical node, certainly, needs the help of relaying nodes the most. Thus, deploying the relaying node at the location that is in most demand can be the best for performance improvement. In other words, a relaying node is located as near to the critical node as possible to relieve the critical node from its relaying tasks.

To investigate the second method of deployments, we examined the relation between positions of nodes and their energy expenditure after the assigned routing task was accomplished. Experimenting many different networks to get the data on energy amounts and location information, we conducted a smoothing method on those data to identify their relationship [12]. Using Fig.1, we try to characterize any relationship between crowded regions and specific locations. We then attempt to identify the appropriate location of a relaying node. Fig.1 illustrates the regions where the critical nodes have most frequently been located. The data used in Fig.1 is from networks with a medium density, density 0.5.

In brief, the second property is that the nodes of inner regions might need the help of relaying nodes the most. We decided to place a relaying node at the position that is closet to the most inner node to achieve good improvements.

Figure 1. Distribution of energy dissipated regions. The x-axis and y-axis denote the proportions of x and y positions to the whole network size, and the intense of the color indicates how much the nodes within regions, relatively, dissipate their energy.

The left figure of Fig. 1, which is from the centralized algorithm, depicts the nodes at the regions near the center node dissipate their energy quickly. The right figure, which is from the localized algorithm, illustrates that the energy dissipation is spread over more regions, compared to the left figure, and there are a couple of regions with the most energy dissipated nodes, rather than one region. The analysis for this phenomenon is that the centralized routing algorithm assumes the global knowledge of the network and thus intelligently figures out the near optimal paths while the localized routing algorithm results in higher energy-consumption, because of relying on only local information of one-hop neighbors, and produces multiple crowded regions. The result of energy balancing from the centralized algorithm is shown in Fig. 2; particularly, we confirmed that the nodes most energy dissipated are located at the inner regions, rather than outer regions. The energy dissipation from the centralized algorithm (Left) is compared to the case using the minimal energy routing of the standard Dijkstra algorithm (Right), in Fig.2.

Figure 2. Comparison of energy balancing between the centralized algorithm and the minimal energy routing in networks with 100 nodes. The x-axis ranks the nodes according to the energy expenditure, and the y-axis is the amount of energy expenditure (J) of nodes with the ranks.

In our centralized algorithm, there are about 20 nodes among 100 nodes that dissipated the most amount of energy (about 94 J), as opposed to the case of only one node (consumed about 250J) in the case of the Dijkstra's minimal energy routing algorithm.

As a whole, as shown in Fig.1 and Fig 2, the most inner regions are prime candidates where a new relaying node can maximally relieve the relaying tasks of the crowded region and result in overall energy balancing.

The third property is that placing a new node to the sparsest region can help energy saving in wireless ad-hoc networks. The sparsest region has been discussed in many other network coverage algorithms. The intuition about this property is that a relaying node between two far nodes helps saving of the required energy for communication since the energy required by a node to transmit a packet to another node with distance r is proportional to r^d for some d (in worst case, larger than 4).

B. Identifying Regions

To find the location complying with the first property, we rank the nodes according to the dissipated energy after the assigned task is accomplished. Then, a new node is positioned as near to the critical node as possible to relieve the critical node from its relaying task.

To find the most inner region for applying the second property, we rank the node according to the extent of the closeness to the center. A simple and intuitive way to be used for assigning a node the extent of the closeness to the center is as follows. First, each node is given the sum of the Euclidean distances to all the other nodes in the network. It is apparent that the node in the center has the smallest sum of distances to all other nodes in the network. As a result, the center node is determined by the minimum value among those assigned values. Then, a new node is positioned as near to the center node as possible to relieve the center node from its relaying tasks.

To find the sparsest region, the Delaunay triangulation is applied [11]. To apply the Delaunay triangulation, we assume that there are not four nodes that are co-circular, which is required in using the Delaunay triangulation. We first review the definition of Delaunay triangles. We perform the triangulation for a set of points, nodes in a network, such that no point is inside the circum-circle of any triangle. In other words, if the circum-circle of a triangle does not contain any node in the interior, the triangle is called the Delaunay triangle. According to this empty circle property of the Delaunay triangle, the largest circum-circle that does not contain any node gives the idea about the sparsest region. We conduct the Delaunay triangulation for the nodes in a network and then rank the radii of the circles to find the center of the largest radius. Specifically, the center of the largest circum-circle becomes the candidate of the sparsest region. However, one drawback of this method is that the location selected by the Delaunay triangulation tends to be close to border edges, which is not beneficial. To avoid this drawback, some portion of border edges of a network is excluded in finding the candidates; for example, in this paper 25% is used. In the placement phase of the additional node, a relaying node is set to the position with the sparsest region according to the center of the largest circum circle of the triangles.

IV. COMAPARISON BETWEEN GAINS

The goal is to achieve as much energy balancing as possible by adding a relaying node that is sorely used for forwarding tasks without making its own traffic. In order to evaluate the effectiveness of the properties we use simulations. The simulations are conducted on randomly deployed networks. In

all cases we add a single node after learning phases. We compare each improvement with the predefined threshold value. The traffic pattern used is the peer-to-peer, and seven different network densities, measured by the number of nodes in a square meter, are examined. Each simulation is repeated more than 30 times in different networks, and the average is recorded. Higher improvement results in better energy balancing and longer network lifetime.

A. The 1st property: Helping critical node

The simulations are conducted at networks with 30, 60 and 100 nodes and with seven different densities varying from 0.2 to 1.0. Table 1 and Table 2 show the results of performance gains by helping the critical node over the centralized algorithm C-Limax and localized algorithm L-Limax, respectively. The numbers of performance gains in the tables denotes **improvement** from the *Metrics* section. The first row is network density, and the first column is the number of nodes deployed in networks.

TABLE I. IMPROVEMENT OVER C-LIMAX BY HELPING CRITICAL NODE

Nodes \ Density	0.2	0.3	0.4	0.5
30	0.0727	0.0825	0.083	0.0943
60	0.0699	0.0707	0.0702	0.064

Nodes \ Density	0.6	0.7	1.0	Threshold
30	0.091	0.1169	0.1069	0.033
60	0.098	0.1032	0.1147	0.017

TABLE II. IMPROVEMENT OVER L-LIMAX BY HELPING CRITICAL NODE

Nodes \ Density	0.2	0.3	0.4	0.5
30	0.2106	0.1873	0.1779	0.1677
60	0.0929	0.1024	0.1047	0.1024

Nodes \ Density	0.6	0.7	1.0	Threshold
30	0.143	0.1432	0.1425	0.033
60	0.1037	0.1004	0.1033	0.017

Fig. 3 illustrates the improvements for the case of networks with 100 nodes.

In Table 1 and the left graph of Fig.3, when C-Limax is used, the improvements of 9.4%, 6.4% and 5.5% are shown for medium density networks, density 0.5, with 30, 60, and 100 nodes. Those results are about three times, four times, and five times of the predefined threshold values, respectively. On the other hand, when L-Limax is used, in Table 2 and the right graph of Fig.3, the improvements of 16.7%, 10.2% and 5.8% are shown for density 0.5 networks with 30, 60, and 100 nodes. These are about five times of the predefined threshold values.

On the whole, the performance gains by helping the critical nodes are decent. In particular, in the case of the centralized algorithm the improvement tends to slightly increase as density gets larger.

Figure 3. Performance gain vs. Density of networks with 100 nodes by helping the critical node over C-Limax (Left) and L-Limax (Right). The horizontal lines indicate the **threshold** values, defined in the *Metrics* section.

From Table 1, Table 2 and Fig. 3, the effect of adding a node to the region in greatest demand is apparent in terms of energy balancing or lifetime extension. To further examine this property, we attempt to know the effect of adding a node to the 2nd, 3rd greatest demand regions. In other words, after identifying the corresponding regions (of the 1st energy dissipated node, 2nd energy dissipated node, 3rd, and so on), we add a new relaying node at the nearest position of the 1st energy dissipated node in the first round, and after the assigned task is accomplished, we compute the improvement and reset the network setting to the right before the first round, and then, we run the second round. In the second round, we add a new node at the region in 2nd greatest demand, and so forth.

Figure 4. Performance gain vs. nodes with ranks by energy dissipation over C-Limax (Left) and L-Limax (Right). The horizontal lines indicate the **threshold** values.

Fig. 4 shows the results of improvement by helping the nodes ranked according to dissipated energy each time one by one, in the case of the centralized and localized routing algorithms, and the number of nodes is 100. The x-axis ranks the nodes according to the dissipated energy. The y-axis denotes the performance gain, improvement, by helping the node with the rank at the x-axis. The simulations are conducted up to the half of the nodes in the networks. In both results of the centralized and localized algorithms, helping the most dissipated node shows more than five times and the rest are gradually decreasing, which indicates that this property is beneficial. In the case of localized algorithm, density 0.5 networks take advantage of any relaying nodes within 50 ranks.

B. The 2nd property: Helping center node

Table 3 shows the results of performance gains by helping the center node over C-Limax. The simulations are conducted

at networks with 30, 60 and 100 nodes (1st column of the tables) with seven different node densities varying from 0.2 to 1.0 (1st row of the tables).

TABLE III. IMPROVEMENT OVER C-LIMAX BY HELPING CENTER NODE

Nodes \ Density	0.2	0.3	0.4	0.5
30	0.0369	0.0534	0.0476	0.0116
60	0.0311	0.0240	0.0239	0.0156
100	0.0173	0.0164	0.0161	0.0253

Nodes \ Density	0.6	0.7	1.0	Threshold
30	0.0247	0.0235	0.0112	0.033
60	0.0144	0.0160	0.0103	0.017
100	0.0195	0.0136	0.008	0.01

Overall, in low and medium density networks, this placement method produces the improvements of just above the threshold values. However, in dense networks this method of placing a node at the most inner position does not perform well. The analysis for this phenomenon is that the denser a network, the harder to identify the crowded regions, and simply placing a node at a center position does not result in the extension of lifetime, especially in dense networks.

Similarly, Table 4 shows the results of performance gains by placing a single relaying node to the inner positions over L-Limax.

TABLE IV. IMPROVEMENT OVER L-LIMAX BY HELPING CENTER NODE

Nodes \ Density	0.2	0.3	0.4	0.5
30	0.1830	0.1564	0.1383	0.126
60	0.0976	0.0907	0.0732	0.0863
100	0.0249	0.0404	0.0436	0.0447

Nodes \ Density	0.6	0.7	1.0	Threshold
30	0.1043	0.102	0.0913	0.033
60	0.0734	0.0751	0.0586	0.017
100	0.0417	0.0377	0.043	0.01

When L-Limax is applied, higher improvements are shown than in the case of C-Limax. Compared to the predefined threshold values, about four times higher improvements are achieved. Also, in low-density networks with small nodes higher improvement is indicated; however, the extent of improvement gets smaller as the size of network increases.

In sum, given a topological layout, adding a node to the most inner region is beneficial only in low- and medium-density networks over C-Limax. Over L-Limax, this method produces decent improvements, about four-fold of the threshold values.

To further examine this innerness property, we attempt to know the effect of adding a node to the 2nd, 3rd inner regions. In other words, after identifying the corresponding regions (the 1st inner node, 2nd inner node, 3rd, and so forth), we add a new relaying node at the position of the 1st inner node in the first round and after the assigned task is accomplished, we compute

the improvement and reset the network to the right before the first round. Then, we run the second round. In the second round we add a new node at the region of the 2nd inner region, and so forth.

Figure 5. Performance gain vs nodes with ranks by innerness over C-Limax (Left) and L-Limax (Right). The horizontal lines indicate the *threshold* values.

Fig. 5 shows the result of improvement by placing relying nodes ranked by inner-ness each time one by one, in the case of the centralized and localized routing algorithms. The y-axis denotes performance gains, improvement, by helping nodes with the ranks at the x-axis, where the rank is based on the inner-ness of a node. The simulations are conducted up to the half of the nodes in networks. In the results of the centralized algorithm, helping the most inner node shows about two and half times of the threshold value. Except a few nodes with top innerness, the rest are almost decreasing in terms of the improvement, and become negligible. Over the localized algorithm, 0.5 density networks shows the improvements of more than four times when helping the most inner node and more than three times with relaying nodes within 50 ranks. We noticed that through the localized algorithm the crowded regions are rather spread out, as shown in Fig 1, and In the localized algorithm the effect of inner-ness property works to many inner nodes, not only the most inner node.

C. The 3rd property: Adding a node at sparsest

The next result shows the performance gains by adding a node to the sparsest regions. Table 5 and Table 6 show the results of performance gains by placing a single node at the sparsest location at networks with 30 and 60 nodes over C-Limax and L-Limax, respectively. Fig. 6 shows the improvements for the case of networks with 100 nodes.

On the whole, from Table 5, Table 6, and Fig. 6, the method of placing a node at the sparsest location produces barely the improvements of the predefined threshold values only in sparse networks. As density grows, this method does not perform well in both the centralized and localized algorithms. Although a relaying node deployed between two far nodes might be able to save the energy for communication of the two nodes, the amount of energy saving has not been connected to the extension of lifetime of a network over our energy-balancing centralized and localized routing protocols, especially in dense networks.

TABLE V. IMPROVEMENT OVER C-LIMAX BY ADDING AT SPARSEST

Nodes \ Density	0.2	0.3	0.4	0.5
30	0.0513	0.0296	0.020	0.0192
60	0.0229	0.0221	0.0179	0.0126

Nodes \ Density	0.6	0.7	1.0	Threshold
30	0.0134	0.0222	0.0286	0.033
60	0.0053	0.0042	0.0135	0.017

TABLE VI. IMPROVEMENT OVER L-LIMAX BY ADDING AT SPARSEST

Nodes \ Density	0.2	0.3	0.4	0.5
30	0.0632	0.0466	0.036	0.0242
60	0.0208	0.0258	0.0288	0.0254

Nodes \ Density	0.6	0.7	1.0	Threshold
30	0.0188	0.0157	0.0112	0.033
60	0.0089	0.0167	0.0103	0.017

Figure 6. Performance gain vs. Density of networks with 100 nodes by adding at the sparsest. The horizontal lines indicate the **threshold** values.

Figure 7. Performance gain vs. node with ranks by sparseness over C-Limax (Left) and L-Limax (Right) routing. The horizontal lines indicate the **threshold** values.

In Fig.7, the y-axis denotes improvement by placing a single node at the location with the rank at the x-axis, where the rank is based on the sparse-ness of the region.

Fig.7 illustrates the result from placing a node at the regions ranked by sparse-ness each time one by one, over C-Limax and L-Limax, and the number of nodes is 100. The simulations are conducted up to the half of the nodes in networks. In medium density, density 0.5, this third method over the centralized algorithm shows the performance below the threshold value as a whole. Likewise, this method over the localized algorithm

does not show any positive effect in medium density, density 0.5, networks as well.

V. CONCLUSION

We have studied the methods of deploying a single relaying node in wireless ad-hoc networks running energy-efficient routing protocols, to further improve the operational lifetime. We have reported the extent to which the improvement could be achieved over the energy-efficient routing protocols depending on the network size and density. Our methods, which are intuitive and simple to be easily used in practice, can be applied to other energy-efficient routing protocols. The results from our methods can be useful for the post-placement problems of hierarchical networks. A direction for future work is to investigate other more beneficial properties and to connect them to the number of multiple nodes while considering per unit cost for maximizing the improvement.

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