Optimal Hierarchical Energy Efficient Design for MANETs

Wasim El-Hajj
Western Michigan University Kalamazoo, MI
welhajj@cs.wmich.edu

Dionysios Kountanis
Western Michigan University
Kalamazoo, MI, USA
kountan@cs.wmich.edu

Ala Al-Fuqaha
Western Michigan University
Kalamazoo, MI, USA
alfuqaha@cs.wmich.edu

Hani Harbi
UAE University
United Arab Emirates
Hharbi@uaeu.ac.ae

ABSTRACT
Due to the growing interest in mobile wireless Ad-Hoc networks' (MANETs) applications, researchers have proposed many routing protocols that differ in their objective. Energy efficiency and scalability are two of the most important objectives. In our previous work, we proposed a fuzzy based hierarchical energy efficient routing protocol (FEER) for large scale MANETs that aims to maximize the network's lifetime and increase its scalability. The problem has two parts: the clustering part and the routing part. In the first part, we cluster the network into two levels of hierarchy (cluster heads and normal nodes), connect the cluster heads (backbone) with each other, and connect the normal nodes to the cluster heads while maximizing the network lifetime. In the second part, we design energy efficient routing that uses the hierarchical structure. We call the first part, the energy efficient clustering problem (EEC). In this paper, we formulate three variations of EEC as integer linear programming (ILP) problems. We first consider a network with a fully connected backbone (EEC-FCB). Then, we relax the fully connected constraint and consider a network with a connected backbone (EEC-CB), not necessarily fully connected. Finally, we consider a more reliable network (EEC-R) by electing a backup cluster head for each cluster.

Categories and Subject Descriptors
C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.4 [**Computer Systems Organization**]: Performance of Systems.

General Terms
Design, performance, theory.

Keywords
Mobile wireless ad-hoc network, hierarchical design, energy efficiency, and integer linear programming.

1. INTRODUCTION
An Ad-Hoc network is a collection of autonomous arbitrarily located wireless hosts (also called nodes), in which an infrastructure is absent. The network consists of nodes, which act as routers in the network. In other words, a node is not only responsible for sending and receiving its own data, but it also has to forward traffic to other nodes.

The major advantages of Ad-Hoc networks are rapid deployment, robustness, flexibility and support for mobility, which are useful in a wide range of applications. Ad-Hoc networks are suitable in situations where an infrastructure doesn't exist or is expensive to deploy.

A typical application is disaster recovery, where the communication network infrastructure is destroyed and restoring communication quickly is important. Another widely used application is military communication in hostile environments (battlefield). Troops will be able to set up a communication network using light weight wireless equipment in rapidly changing environments.

A critical issue in the design of routing protocols for mobile wireless Ad-Hoc networks (MANETs) is the efficient utilization of resources such as limited energy. The problem becomes more challenging if the network is deployed in large scale. In order to utilize the limited energy resources and to overcome the scalability problem that is inherent in flat networks [1, 2], we previously designed a fuzzy based hierarchical energy efficient routing protocol (FEER) that aims to maximize the lifetime of the network [3]. The lifetime of the network is decided by the lifetime of the weakest node i.e. the node with the shortest time to survive.

FEER organizes the network into two levels of hierarchy (normal nodes' level and cluster heads' level). Initially, FEER elects some nodes in the network to act as cluster heads (CHs). It interconnects CHs to each other forming the network backbone. Then, it associates each normal node with a CH. And finally it designs the routing scheme. FEER has two major components: (1) the first component is to cluster the network such that the initial backbone nodes are powerful enough to handle the traffic demand; (2) the second component designs the routing scheme and the maintenance scheme.

In this paper, we only consider the first component (the clustering part). We define the optimal solution to the energy efficient clustering problem when the network has a fully connected backbone (EEC-FCB) by formulating it as an ILP problem. To make the problem more practical, an extension to EEC-FCB is made in order to reduce the backbone connections (EEC-CB). The ILP solutions of EEC-FCB and EEC-CB are compared with each other and the data are analyzed. We also introduce another extension in order to make the network more reliable (EEC-R). EEC-R introduces a backup CH for each cluster. In a situation where the CH fails, weakens, or moves outside its cluster coverage, the backup cluster head (BCH) takes over immediately. BCHs are very useful in networks that are very mobile. It is worth noting that the ILP formulation is used as a theoretical basis and it is not intended to be used in practice. Our proposed ILP formulation finds the optimal clustering solution. Researchers can then compare their clustering approaches to our ILP formulation in order to evaluate the performance of their schemes.

The remainder of this paper is organized as follows. Section 2 includes some related work done in energy efficient routing in MANETs. Section 3 presents an overview of FEER. Section 4 defines the energy efficient clustering problem with a fully connected backbone (EEC-FCB) and its ILP formulation. Section 5 defines the energy efficient clustering problem with a relaxed backbone (EEC-CB) and its formulation. Section 6 presents the performance evaluation of EEC-FCB and EEC-CB. Section 7 describes the reliable energy efficient clustering problem (EEC-R) and its formulation. Section 8 concludes the paper and discusses future work.

2. RELATED WORK

Researchers have proposed many routing protocols that address the limited energy constraint found in MANETs [4-14]. Some of this work focuses on minimizing the total energy consumption rate of the network. However, this can lead to some nodes in the network being drained out of energy very quickly. Hence, instead of trying to minimize the total energy consumption, routing to maximize the network's lifetime is considered [4-8].

In [4] and [5], a rigorous formulation using linear programming is presented which attempts to capture the issue of power consumption more precisely. The objective was to design the routing while maximizing the network lifetime. They give heuristic algorithms to solve the linear program approximately, but the proposed approach can perform arbitrarily bad in the worst case. In a later paper [6], a centralized algorithm to determine the maximum lifetime is presented, based on the Garg-Koenemann [7] algorithm for multicommodity flow.

In [8], the authors consider the routing problem in MANET with the goal of maximizing the lifetime of the network. They propose a distributed routing algorithm that reaches the optimal (centralized) solution to within an asymptotically small relative error. Their approach is based on the formulation of multicommodity flow, and it allows considering different power consumption models and bandwidth constraints. It works for both static and slowly changing dynamic networks.

Our energy efficient approach has some similarities with other approaches in the sense that it designs the network in a hierarchical fashion and then it achieves interconnectivity between various parts of the network. But to our knowledge nobody formulated this design problem as an ILP problem and analyzed its performance. In the next section, we give a brief overview about FEER.

3. FEER OVERVIEW

FEER protocol [3] is a hierarchical energy efficient routing scheme for large scale mobile ad-hoc networks that aims to maximize the network's lifetime. Each node in the network is characterized by its residual energy, traffic, mobility, and degree. In [3], we developed a fuzzy logic controller that combines these parameters, keeping in mind the synergy between them. Having known the quality of each node, a centralized algorithm is used to cluster the network into two groups (cluster members and cluster heads) and then route messages between nodes. FEER also creates an extra type of nodes called guest nodes that are beneficial in minimizing cluster maintenance. In this paper we remove the guest nodes in order to reduce the complexity of the ILP formulation.

FEER differs from other approaches in the following aspects: (1) it uses a fuzzy logic controller to evaluate the strength of each node. (2) It designs a fault tolerant backbone that satisfies the network communication demand. (3) It designs energy efficient routing that maximizes network lifetime. FEER achieves its goals by using many algorithms such as: dominating set like algorithm, min cut algorithm, max flow algorithm, and routing algorithm. The complexity of FEER is bounded by the complexity of the min cut algorithm which is $O(n^3)$.

4. ENERGY EFFICIENT CLUSTERING WITH FULLY CONNECTED BACKBONE (EEC-FCB) AND ILP FORMULATION

In this section, we define and formulate the energy efficient clustering problem when the network has a fully connected backbone (EEC-FCB). We formulate EEC-FCB as an ILP problem, where every function must be linear, and the solutions of every variable must be integer. In EEC-FCB, every variable can be either 0 or 1 and thus the formulation is called binary ILP formulation.

4.1 EEC-FCB definition

Since flat networks have poor scalability [1, 2], we designed our network in a hierarchical fashion. Two hierarchical levels are used: cluster heads (CHs) level and normal nodes level. Normal nodes can only communicate with their corresponding CHs, while CHs communicate with each other. The EEC-FCB problem is to group a large set of mobile Ad-Hoc nodes into clusters, elect a CH for each cluster, connect cluster nodes to the chosen cluster heads, and fully connect CHs with each other (this condition will be relaxed in section 5) while maximizing the network lifetime. The radio model we use follows the most commonly used power-attenuation model [15]. The signal power falls as $1/r^k$, where r is the distance between the transmitter/receiver nodes and k is a real constant dependent on the wireless environment, typically between 2 and 4. In our case, we set $k = 2$ for communication between normal nodes and CHs, and $k = 3$ for communication between CHs. The rationale for using more power consumption between CHs ($k = 3$) is that CHs bare more burden than normal nodes and they are supposed to route all the traffic that is generated from their cluster members.

4.2 EEC-FCB ILP formulation

To make the ILP formulation easy to follow, we start by introducing the notations used in the formulation. The constants/variables and their definitions are presented as follows:

- N: Total number of nodes in the network – predetermined.
- P: Number of clusters heads – predetermined.
- d_{ij}: Euclidean distance between nodes i and j.
- K_j: Max number of nodes that can be connected to CH j – predetermined.
- c_{ij}: Cost of connecting a regular node i to CH j (proportional to d_{ij}^2).
- h_{jk}: Cost of connecting CH j to CH k (proportional to d_{jk}^3).
- b_j: Weight associated with CH j.
- x_{ij}: Variable. 1 if node i is connected to CH j; 0 otherwise.
- z_{jk}: Variable. 1 CH j is connected to CH k; 0 otherwise.
- y_j: Variable. 1 if node j is chosen to be a CH; 0 otherwise.
- w_{ij}: Variable. 1 if $x_{ij} = 1$and $y_j = 1$; 0 otherwise.

Note that b_j can be any meaningful weight assigned to a node (an appropriate weight is discussed in [3]). The higher the value of b, the better the node is. Since the objective function is a minimization function, each value in the b array is multiplied by -1. EEC-FCB can be formulated as a binary ILP problem as follows:

$$\underset{x,y,z}{Min}$$

$$(\sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij}x_{ij} + \sum_{j=1}^{N} b_j y_j + \sum_{j=1}^{N}\sum_{k=1}^{N}(h_{jk} - c_{jk})z_{jk})$$

Subject to:

$$\sum_{i=1}^{N} x_{ij} \geq (P-1)y_j + (1-y_j)\,; \qquad \forall j \qquad (1)$$

$$\sum_{i=1}^{N} x_{ij} \leq (K_j + P - 1)y_j + (1-y_j)\,; \qquad \forall j \qquad (2)$$

$$\sum_{i=1}^{N}\sum_{j=i+1}^{N} x_{ij} = (N-P) + P(P-1)/2\,; \qquad (3)$$

$$\sum_{j=1}^{N} y_j = P\,; \qquad (4)$$

$$\sum_{\substack{k=1 \\ j\neq k}}^{N} z_{jk} = (P-1)y_j\,; \qquad \forall j \qquad (5)$$

$$\sum_{\substack{j=1 \\ j\neq k}}^{N} z_{jk} = (P-1)y_k\,; \qquad \forall k \qquad (6)$$

$$\sum_{i=1}^{N} x_{ii} = 0\,; \qquad (7)$$

$$x_{ij} = x_{ji}\,; \qquad \forall i; \forall j \qquad (8)$$

$$w_{ij} \leq x_{ij}\,; \qquad \forall i; \forall j \qquad (9)$$

$$w_{ij} \leq y_j\,; \qquad \forall i; \forall j \qquad (10)$$

$$w_{ij} \geq x_{ij} + y_j - 1\,; \qquad \forall i; \forall j \qquad (11)$$

$$\sum_{i=1}^{N} w_{ij} \geq 1\,; \qquad \forall j \qquad (12)$$

$$\sum_{i=1}^{N} w_{ij} \leq (P-1)y_j + (1-y_j)\,; \qquad \forall j \qquad (13)$$

$$x_{ij} \in \{0,1\}\,; \qquad \forall i; \forall j \qquad (14)$$

$$z_{jk} \in \{0,1\}\,; \qquad \forall j; \forall k \qquad (15)$$

$$y_j \in \{0,1\}\,; \qquad \forall j \qquad (16)$$

Note that variables *i*, *j*, and *k* are between *1*and *N*. The objective function is divided into three parts. The first part calculates the cost of connecting normal nodes to CHs. The second part calculates the cost of electing CHs. The third part calculates the cost of connecting CHs with each other. By minimizing the objective function, the power consumption rate is optimized and the lifetime is maximized.

Constraint 1 indicates that if node *j* is chosen to be a CH, it needs to support at least *(P-1)* other CHs. Constraint 2 indicates that if node *j* is chosen to be a CH, it should be connected to at most *(P-1)* CHs and K_j regular nodes. Constraints 1 and 2 also indicate that if node *j* is a normal node, it should be connected to only one CH. Constraint 3 indicates that the total number of interconnections is equal to the number of connections between regular nodes and CHs plus the number of connections that fully connect the CHs. Constraint 4 indicates that the total number of CHs is *P*. Constraints 5 and 6 make sure that matrix *z* (backbone) contains only the connections that interconnect CHs. Constraints 7 and 8 indicate that matrix *x* is symmetric and its diagonal is 0. Constrains 9, 10, and 11 indicate that w_{ij} = 1 only if both x_{ij} = 1 *and* y_j = 1, 0 other wise. w_{ij} is used to simulate x_{ij} x y_j .

Constraints 12 and 13 ensure that if a node is chosen to be a regular node, it should be connected to only one CH and not to another regular node. Constraints 14, 15, and 16 indicate that the variables have binary values. Figure 1 shows the outcome of EEC-FCB on a network of 9 nodes. Nodes 1, 2, and 3 are elected as CHs. Nodes 4 and 5 join CH 1. Nodes 6 and 7 join CH 2. Nodes 8 and 9 join CH 3. In the next section, we extend EEC-FCB such that the backbone connections are reduced.

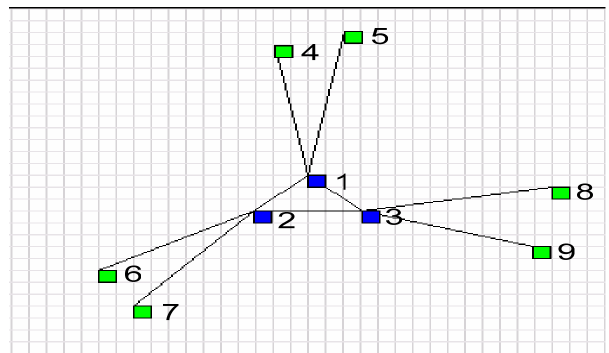

Figure 1: EEC-FCB for a network of 9 nodes.

5. ENERGY EFFICIENT CLUSTERING WITH CONNECTED BACKBONE (EEC-CB) AND ILP FORMULATION

EEC-FCB (section 4) assumes that the backbone network is fully connected. To make the network more practical, we relax this constraint and reduce the backbone connections while ensuring the network connectivity. One way to ensure the backbone connectivity is to connect one CH with all the other CHs. We call such a CH the main cluster head (MCH). Note that, if a node is a MCH, then it is definitely a CH. If a node is a CH, then it might or might not be a MCH. If a node is a normal node, then it is neither a CH nor a MCH. We introduce a new variable called M_j, where M_j = 1 if node *j* is a MCH; 0 otherwise. Some of the constraints discussed in section 4 remain the same, while others are added. EEC-CB is presented by the following binary ILP problem:

$$\underset{x,y,z}{Min}$$

$$(\sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij}x_{ij} + \sum_{j=1}^{N} b_j y_j + \sum_{j=1}^{N}\sum_{k=1}^{N} h_{jk}z_{jk})$$

Subject to:

$$M_j \leq y_j\,; \qquad \forall j \qquad (17)$$

$$M_j \in \{0,1\}\,; \qquad \forall j \qquad (18)$$

$$\sum_{j=1}^{N} M_j = 1; \tag{19}$$

$$\sum_{i=1}^{N} x_{ij} \geq (P-2)M_j + 1; \qquad \forall j \tag{20}$$

$$\sum_{i=1}^{N} \sum_{j=i+1}^{N} x_{ij} \leq (N-P) + P(P-1)/2; \tag{21}$$

$$\sum_{\substack{k=1 \\ j \neq k}}^{N} z_{jk} \geq (P-2)M_j + y_j; \qquad \forall j \tag{22}$$

$$\sum_{\substack{k=1 \\ j \neq k}}^{N} z_{jk} \leq (P-1)y_j; \qquad \forall j \tag{23}$$

$$z_{jk} = x_{kj}; \qquad \forall j; \forall k \tag{24}$$

Constraints 2, 4, and 7 through 16 are also needed to formulate EEC-CB. Constraints 17 and 18 indicate that if a node is chosen as a MCH ($M_j = 1$), then it must be a CH ($y_j = 1$) but the inverse is not true (discussed above). Constraint 19 indicates that there should be one MCH in the network. This condition ensures the connectivity of the backbone. Constraint 20 indicates that if a node was chosen as a MCH, then it must be connected to at least (*P-1*) other CH. Otherwise, the node is just a normal node or a CH. If it was a normal node ($M_j = 0$), it should be connected to exactly one CH. If it was a CH, it should be connected to at least one other CH. Constraint 21 is the same as constraint 3, but with the equal sign changed to less than or equal. In this case, the backbone network is not fully connected. Constraints 22 and 23 ensure that the MCH is connected to all other CHs, while normal CH can be connected to a minimum of one other CH. Constraint 24 indicates that the *z* matrix (backbone) is symmetric; Figures 2 and 3 display two sample executions of EEC-CB.

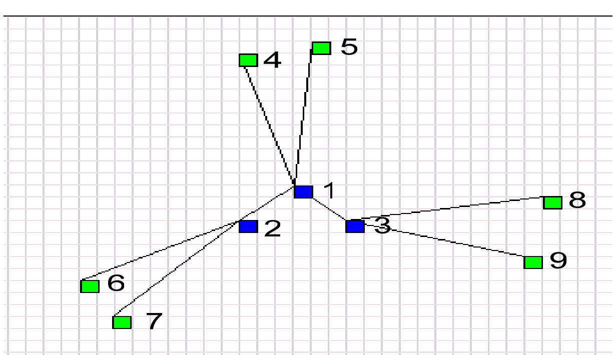

Figure 2: EEC-CB for the same network presented in Figure 1.

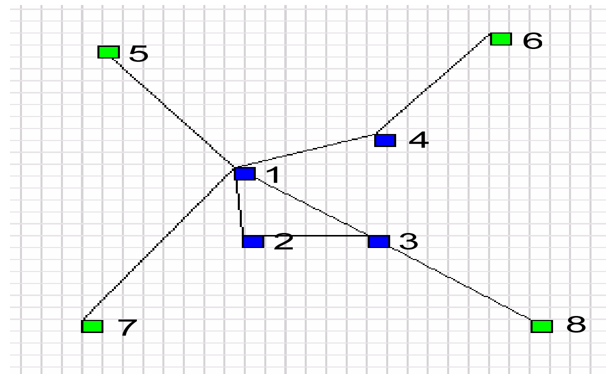

Figure 3: EEC-CB for a network of 8 nodes.

6. PERFORMANCE EVALUATION

In this section we evaluate the performance of EEC-FCB and EEC-CB. Networks of different sizes and considered. For each network, *n* nodes are uniformly distributed in a 600^2 unit space. The average of *K* runs is calculated for each network. Because EEC-FCB and EEC-CB takes lots of time to execute (NP-complete), we only considered networks with less than ten nodes. Figure 4 shows the results.

EEC-FCB and EEC-CB produce networks with close costs. But, EEC-CB has a lower cost because it designs a network with relaxed backbone i.e. less connections between CHs which translates to less network cost. Note that EEC-FCB and EEC-CB tend to choose as CHs nodes that are close to each other. As the distance between CHs increases, the objective function increases and thus the network cost increases.

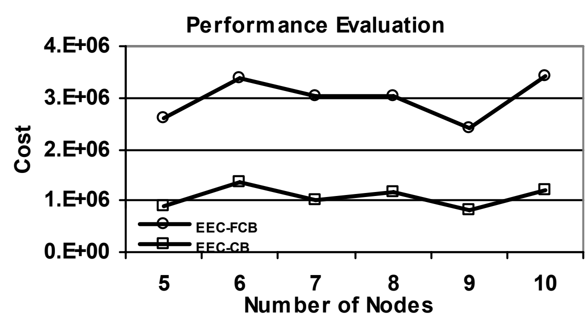

Figure 4: Costs of ILP, and ILP Extension.

7. ENERGY EFFICIENT CLUSTERING WITH A RELIABLE BACKBONE (EEC-R) AND ILP FORMULATION

In this section, we further extend EEC-FCB discussed in section IV so that each cluster will be provided by a backup cluster head (BCH). Having a BCH is very useful in many situations such as: (1) CH's energy becomes scarce and it can not handle the cluster demand. (2) CH is not able to cover all the nodes in its cluster because of mobility. (3) Connectivity between CHs is broken also because of mobility. (4) CH fails.

7.1 EEC-R definition

EEC-R is to group a large set of nodes into clusters, elect each CH, elect each BCH, connect nodes to the chosen CHs and to the chosen BCHs, and fully connect CHs and BCHs while minimizing the power consumption rate and maximizing the network lifetime. Note that the backbone connections can be reduced using the same technique used in section 5.

7.2 EEC-R ILP formulation

The constants/variables notations given in section 4 are still the same with w_{ij} removed and three new variables added. The new variables are presented as follows:

- w_j: Variable. 1 if node j is chosen to be a BCH, 0 otherwise.
- t_{ij}: Variable. 1 if both $x_{ij} = 1$ and $y_j = 1$, 0 otherwise.
- v_{ij}: Variable. 1 if $x_{ij} = 1$ and $w_j = 1$, 0 otherwise.

The objective function presented in section 4 is still the same. EEC-R can be formulated as the following binary ILP problem:

$$\underset{x,y,z}{Min}$$

$$\left(\sum_{i=1}^{N}\sum_{j=1}^{N} c_{ij}x_{ij} + \sum_{j=1}^{N} b_j y_j + \sum_{j=1}^{N}\sum_{k=1}^{N}(h_{jk} - c_{jk})z_{jk}\right)$$

Subject to:

$$y_j + w_j \le 1; \quad \forall j \tag{25}$$

$$y_j \ge 0; w_j \ge 0; \quad \forall j \tag{26}$$

Constraints 25 and 26 make sure that if a node is chosen to be a CH, then it can not be a BCH. And if a node is chosen to be a BCH, then it can not be a CH.

$$\sum_{i=1}^{N} x_{ij} \ge (2P-1)(y_j) + (2P-1)(w_j) + (2)(1-y_j-w_j); \tag{27}$$

$\forall j$, constraint 27 puts a lower bound on the number of connections that node j can make with other nodes. If node j was elected as a CH ($y_j = 1$) or as a BCH ($w_j = 1$), then node j should be connected to at least all the other CHs and BCHs (*2P-1* connections). If node j was a normal node, then it should be connected to its CH and its BCH (2 connections).

$$\sum_{i=1}^{N} x_{ij} \le (K_j + 2P - 1)(y_j) + (w_j)(2P + K_j - 2) + (2)(1 - y_j - w_j); \tag{28}$$

$\forall j$, constraint 28 puts an upper bound on the number of connections that node j can make with other nodes. The same reasoning applied in constraint 27 applies also in this constraint.

$$\sum_{i=1}^{N}\sum_{j=i+1}^{N} x_{ij} = (N-P) + (N-2P) + 2P(P-1); \tag{29}$$

Constraint 29 sums up the connections made between normal nodes and their associated CHs/BCHs plus the connections that fully interconnects the CHs/BCHs.

$$\sum_{j=1}^{N} w_j = P; \tag{30}$$

Constraint 30 indicates that the number of BCH is equal to the number of CHs.

$$\sum_{\substack{k=1 \\ j\ne k}}^{N} z_{jk} = 2(P-1)y_j + 2(P-1)w_j; \quad \forall j \tag{31}$$

$$\sum_{\substack{j=1 \\ j\ne k}}^{N} z_{jk} = 2(P-1)y_k + 2(P-1)w_k; \quad \forall j \tag{32}$$

Constraints 31 and 32 make sure that matrix z contains only the connections that interconnect CHs and BCH (backbone network).

$$t_{ij} \le x_{ij}; \quad \forall i; \forall j \tag{33}$$

$$t_{ij} \le y_j; \quad \forall i; \forall j \tag{34}$$

$$t_{ij} \ge x_{ij} + y_j - 1; \quad \forall i; \forall j \tag{35}$$

Constraints 33, 34, and 35 make sure that t_{ij} = 1only if $x_{ij} = 1$ and $y_j = 1$, 0 otherwise. t_{ij} simulates x_{ij} x y_j.

$$\sum_{i=1}^{N} t_{ij} \ge 1; \quad \forall j \tag{36}$$

$$\sum_{i=1}^{N} t_{ij} \le (P-1)y_j + (1-y_j); \quad \forall j \tag{37}$$

Constraints 36 and 37 are used to ensure that if a node is chosen to be a regular node, then it should be connected to one CH and not to another regular node.

$$v_{ij} \le x_{ij}; \quad \forall i; \forall j \tag{38}$$

$$v_{ij} \le w_j; \quad \forall i; \forall j \tag{39}$$

$$v_{ij} \ge x_{ij} + w_j - 1; \quad \forall i; \forall j \tag{40}$$

Constraints 38, 39, and 40 make sure that v_{ij} = 1only if $x_{ij} = 1$ and $w_j = 1$, 0 otherwise. v_{ij} simulates x_{ij} x w_j.

$$\sum_{i=1}^{N} v_{ij} \ge 1; \quad \forall j \tag{41}$$

$$\sum_{i=1}^{N} v_{ij} \le (P-1)w_j + (1-w_j); \quad \forall j \tag{42}$$

Constraints 41 and 42 ensure that if a node is chosen to be a regular node, then it should be connected to one BCH and not to another regular node.

$$w_j \in \{0,1\}; \quad \forall j \tag{43}$$

$$t_{jk} \in \{0,1\}; \quad \forall j; \forall k \tag{44}$$

$$v_{jk} \in \{0,1\}; \quad \forall j; \forall k \tag{45}$$

Constraints 43, 44, and 45 are used to indicate that the variables are binary values. Figure 5 shows the output of EEC-R on a network of 7 nodes. Nodes 1 and 4 are elected as CHs. Nodes 2 and 3 are elected as BCHs for CHs 1 and 4 respectively. Nodes 5 and 6 are connected to CH 1 and BCH 2. Node 7 is connected to CH 4 and BCH 3. The backbone, composed of CHs and BCHs, is fully connected. And the normal nodes are connected to both CHs and BCHs.

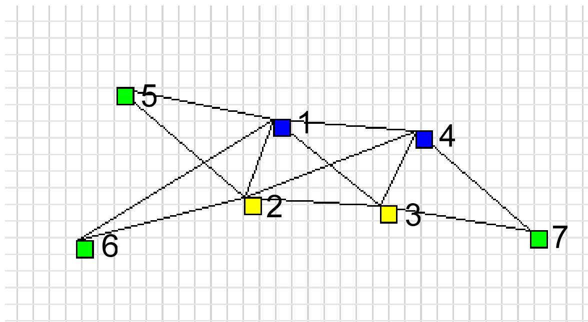

Figure 5: EEC-R for a network of 7 nodes.

8. CONCLUSION AND FUTURE WORK

Due to the vast number of useful applications in MANETs, designing an energy efficient routing protocol for such networks is becoming more and more important. Energy efficiency can be translated into the problem of maximizing the network lifetime. Previously, we proposed a hierarchical protocol (FEER) that aims to maximize network lifetime. In this paper, we describe the optimal solution to the energy efficient clustering problem (EEC) by formulating it as an ILP problem. Three variations of EEC were formulated. EEC-FCB designs a network with a fully connected backbone. EEC-CB reduces the backbone connections while ensuring network connectivity. EEC-R designs a reliable network by introducing a backup cluster head for each cluster. We are now in the process of designing a distributed network design and a distributed routing protocol that achieves the same goals.

9. REFERENCE

[1] Gupta, P. and Kumar, P. R. The Capacity of Wireless Networks. *IEEE Transactions on Information Theory, IT-46,* 2 (March 2000), 388-404.

[2] Gupta, P., Gray, R., and Kumar, P. R. An Experimental Scaling Law for Ad Hoc Networks. (May 16, 2001), http://black1.csl.uiuc.edu/~prkumar/

[3] El-Hajj, W., Kountanis, D., Al-Fuqaha, A., and Guizani, M. A Fuzzy-Based Hierarchical Energy Efficient Routing Protocol for Large Scale Mobile Ad Hoc Networks (FEER). *IEEE International Conference on Communication (ICC'06),* (Istanbul, Turkey, June11-15, 2006).

[4] Chang, J.-H. and Tassiulas, L. Routing for maximum system lifetime in wireless ad-hoc networks. In *Proc. of* 37*th Annual Allerton Conference on Communication, Control, and Computing,* (September 1999).

[5] Chang, J.-H. and Tassiulas, L. Energy conserving routing in wireless ad-hoc networks. In *Proc. of IEEE INFOCOM,* (March 2000), 22–31.

[6] Chang, J.-H. and Tassiulas, L. Fast approximation algorithms for maximum lifetime routing in wireless ad-hoc networks. In *Lecture Notes in Computer Science: Networking 2000, 1815,* (May 2000), 702–713.

[7] Garg, N. and Koenemann, J. Faster and simpler algorithms for multicommodity flow and other fractional packing problems. In *Proc. of the 39th Annual Symposium on Foundations of Computer Science,* (November 1998), 300–309.

[8] Sankar, A. and Liu, Z. Maximum lifetime routing in wireless ad-hoc networks. In *Proc. of IEEE INFOCOM,* (2004).

[9] Lin, CR and Gerla, M. Adaptive Clustering for Mobile Wireless Networks. *IEEE JSAC, 15,* (September 1997), 1265-1275.

[10] Amis, D. and Prakash, R. Load-Balancing Clusters in Wireless Ad Hoc Networks. *Proc. of the 3rd IEEE ASSET'00*, (March 2000), 25–32.

[11] Ryu, J.-H., Song, S., and Cho, D.-H. New Clustering Schemes for Energy Conservation in Two-Tiered Mobile Ad-Hoc Networks. *IEEE International Conference on Communication (ICC'01), 3,* (June 2001), 862–66.

[12] Wu, J. On Calculating Power-Aware Connected Dominating Sets for Efficient Routing in Ad Hoc Wireless Networks. *Journal of Communication and Networks, 4,* 1, (March 2002), 59–70.

[13] Yu, J. Y. and Chong, P. H. J. 3hBAC (3-hop between Adjacent Clusterheads): a Novel Non-overlapping Clustering Algorithm for Mobile Ad Hoc Networks. In *Proc. of IEEE Pacrim'03, 1,* (August 2003), 318–21.

[14] Kawadia, V. and Kumar, P. R. Power control and clustering in ad hoc networks. In *Proc. of IEEE INFOCOM,* (2003).

[15] Rappaport, T.S. *Wireless Communications: Principles and Practices*. Prentice Hall, 1996.