A HIERARCHICAL ENERGY CONSERVATION PROTOCOL IN MANETS

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ABSTRACT

A Mobile Ad Hoc Network (MANET) is a network consisting of a set of mobile hosts. Energy efficiency is a critical issue in MANETs since mobile hosts are with limited energy. Geographical Adaptive Fidelity (GAF) protocol proposed the grid-based architecture based on the idea of connected dominating set. It divides the whole network area into disjoint identical square grids, called virtual grids. In each grid, there is only one node for forwarding packets to achieve power saving. In this paper, we propose the Hierarchical Energy Conservation protocol (HEC). In this protocol, in order to increase the coverage of wireless transmission, it divides the whole network area into disjoint hexagonal grids instead of square grids and employs the hierarchical group control mechanism. Mathematical analysis and simulation results show that the proposed protocol not only prolongs the lifetime of MANETs but also maintains appropriate packet delivery ratio and latency.

KEYWORDS

Connected dominating set, energy efficiency, latency, network lifetime, packet delivery ratio, power saving.

1. INTRODUCTION

MANET becomes popular recently in the field of wireless networks and mobile computing. A MANET is a network consisting of a set of mobile hosts being capable of communicating with each other. Each node is energy-limited, so energy-efficiency becomes an importance issue in MANETs.

Many studies assume that the energy consumption in idle state is approximately equal to that in receiving or transmitting states (Xu, Heidemann and Estrin, 2001:70-84). When a MANET is working, many nodes are idle at most of the time instead of receiving or transmitting. Some routing protocols, such as AODV (Perkins and Royer, 1999:90-100) didn't take into consideration the energy costs of nodes in idle state. Therefore, it has inspired academic research on energy saving. There were many energy efficiency strategies based on connected dominating set, such as SPAN (Chen et al. 2002:481-494) and GAF (Xu, Heidemann and Estrin, 2001:70-84).

In SPAN, the backbone of the whole network was formed by the way of electing coordinators which forward packets for the non-coordinator nodes. GAF divides the network area into many virtual grids, ensuring that within one grid, only one node would be in active state and the other nodes would all be in sleep state to reduce energy consumption. Both SPAN and GAF can reduce energy consumption and thus extend network lifetime.

When most of nodes with high speed are distributed across a MANET, rapid topology changing and coordinator changing of SPAN will result in lots of data exchanges. Thus, this heavy overhead will reduce system performance. Although GAF does not have the overhead like SPAN, its square virtual grid does not approximate to the circular coverage of signal transmission, resulting in a lot of signal overhearing. This will increase probability of collisions, leading to wasting energy.

In this paper, the Hierarchical Energy Conservation (HEC) protocol is proposed. Hexagonal grids are employed, which approximates much more to the circular coverage of signal transmission, and the hierarchical design is used to reduce the number of active nodes by 25%. We have developed two versions of the algorithm. One uses same GAF state transition and employs hierarchical framework (called HEC-bas). The other includes the take-over mechanism in HEC-bas (called HEC-enh). HEC-enh allows more energy conservation and then extends overall network lifetime. Through simple mathematical analysis and volumes of simulation statistics, the two versions of proposed HEC protocol are shown to be energy-efficient for MANETs.

2. RELATED WORK

Employing the concept of connected dominating sets (Das and Bharghavan, 1997:376-380) (Dai and Wu, 2004:908-920) (Wu, 2002:866-881) as the foundation of efficient usage of energy, GAF algorithm is described briefly. The main concept of GAF is to divide the whole network area into many identical virtual grids, and to ensure that there is only one active node in each virtual grid, which will be responsible for packet forwarding. Other nodes will enter sleeping state, and periodically wake up to check whether themselves each is required to be as an active node. To maintain connectivity, GAF requires that any pair of nodes within two adjacent virtual grids can communicate with each other.

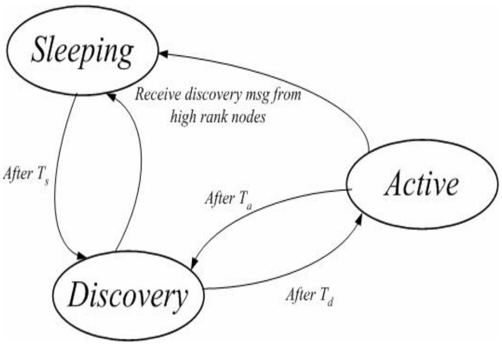

Figure 1. State transition of GAF.

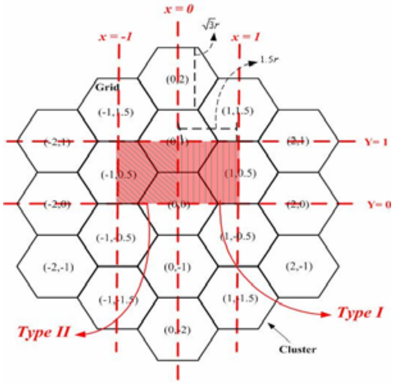

Figure 2. HEC grids, clusters, and the scaled grid coordinate.

In GAF, every node would be in one of three states: active state, discovery state, or sleeping state, as shown in Fig. 1. When the system is initialized, all nodes will be in discovery state. Nodes will activate their communication units, and gather information by exchanging the discovery messages with each other in the same virtual grid.

GAF has designed three timers, T_a, T_d and T_s, which are used for three states, respectively. T_a is used to determine the period during which a node would remain in active state. T_d is used to determine the longest waiting time during which a node would remain in discovery state. T_s is used to determine the sleeping period during which a node would remain in sleeping state. When a node enters discovery state, its T_d timer will be initialized and begin countdown. When the T_d timer reaches zero but the node has not received discovery messages from other nodes, the node enters active state, and initializes its T_a timer, and then broadcasts a discovery message to prevent other nodes in the same virtual grid from entering active state. Otherwise, a discovery message was received from other node before the T_d timer has reached zero. The node then inactivates its communication unit, enters sleeping state, and initializes its T_s timer. Any node in sleeping state will activate their own communication units and enter discovery state after its T_s timer has reached zero. After its T_a timer has reached zero, any node in active state will enter discovery state. If an active node receives the discovery message from other higher rank nodes, it will enter sleeping state.

3. THE HIERARCHICAL ENERGY CONSERVATION PROTOCOL

The HEC design partitions the whole network area into hexagonal grids. A cluster is composed of 19 hexagonal grids, as shown in Fig. 2. In the design of HEC, we demand that any two nodes within any three connected grids must be able to communicate with each other, as shown in Fig. 3. Thus, the maximum side length *r* of each virtual grid can be derived: $r^2+(3\sqrt{3}r)^2\le R^2$ or $r\le(R/\sqrt{28})$, where *R* is the wireless radio propagation range.

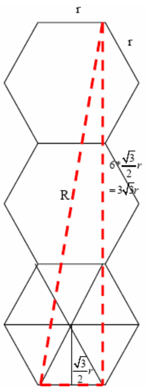

Figure 3. The Side Length.

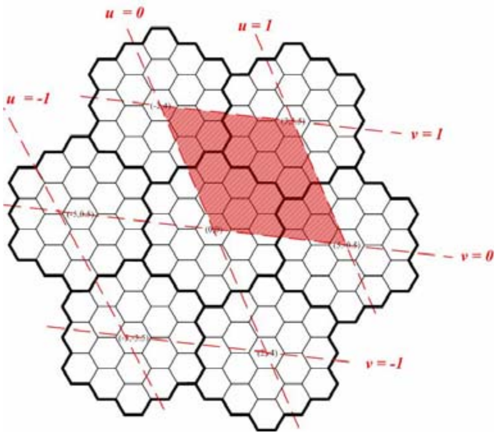

Figure 4. Cluster Coordinates of HEC.

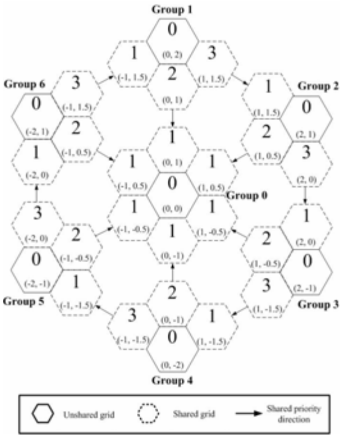

Figure 5. Priorities for HEC groups.

Assuming that the coordinate of central point of simulation area is (0, 0) and each node's coordinate is (*node_X, node_Y*), we propose a conversion method to convert the original coordinate system to the new coordinate system (hereafter referred to as the scaled coordinate system). Let the horizontal coordinate unit be *1.5r*, and the vertical coordinate unit be $\sqrt{3}r$. *node_X* and *node_Y* are divided by *1.5r* and $\sqrt{3}r$, respectively, resulting in its scaled coordinate, represented by (*Xs, Ys*).

We define each grid's coordinate as the scaled coordinate of its central point. The straight lines of *x=i* and *y=j*, where *i* and *j* are integers, will partition the network area into square regions. There are two types of these square regions, type I and type II, as shown in Fig. 2. Let $a=\lfloor X_s\rfloor$ and $b=\lfloor Y_s\rfloor$. If *a* is an even number, then the node (*Xs, Ys*) is within the type I region which is bounded by the central points of the three grids (*a, b*), (*a, b+1*), and (*a+1, b+0.5*). Otherwise, the node (*Xs, Ys*) is within the type II region which is bounded by the central points of the three grids (*a, b+0.5*), (*a+1, b*), and (*a+1, b+1*). After calculating the distances from the node (*Xs, Ys*) to the central points of these three grids in the origin coordinate system, node (*Xs, Ys*) resides in the grid with the shortest distance.

Then, we define each cluster's coordinate as the scaled coordinate of its central point. The straight lines of *y+2x=9.5u*, and *y+0.1x=3.8v*, where *u* and *v* are integers, will partition the whole network area into parallelogram regions. Let $a=\lfloor (Y_s+2X_s)/9.5\rfloor$ and $b=\lfloor (Y_s+0.1X_s)/3.8\rfloor$. The node (*Xs, Ys*) resides in a parallelogram region which is bounded by the central points of four clusters (*5a-2b, -0.5a+4b*), (*5a-2b+5, -0.5a+4b-0.5*), (*5a-2b-2, -0.5a+4b+4*), and (*5a-2b+3, -0.5a+4b+3.5*). For example, in Fig. 4, the shadow parallelogram region is bounded by the central points of clusters (*0, 0*), (*5, -0.5*), (*-2, 4*) and (*3, 3.5*). After calculating the distances from the central point of the grid in which node (*Xs, Ys*) resides to the central points of these four clusters in the origin coordinate system, node (*Xs, Ys*) resides in the cluster with the shortest distance.

The network area is partitioned into grids, where every 19 grids form one cluster. In order to effectively reduce the number of active nodes, our design requires that any pair of nodes within three connected virtual grids need to be able to communicate with each other. We classify grids into shared grids and unshared grids. For convenient explanation, unshared grids are duplicated, as shown in Fig. 5. The shared grids will be represented by dotted hexagons, while solid hexagons will represent unshared grids. Every cluster can be separated into seven groups and each shared grid can be shared by exactly two groups, as shown in Fig. 5. Only one node in each group will be elected as the leader, which will be responsible for forwarding packets. The priority values are between 0 and 3. 0 represents the highest priority, while 3 represents the lowest. Unshared grids are with the highest priority; that is, we have nodes in unshared grids be used first. Because each unshared grid is located in the center of its corresponding group, using the nodes in unshared grids can effectively cover the whole cluster.

3.1 HEC-bas Algorithm

The state transition of HEC-bas is identical to that of GAF (see Fig. 1). When a node enters discovery state, it needs to turn on its communication unit and renew its position information through GPS. It will start listening channels simultaneously and re-calculate its gird id, group id, cluster id, and other information based on the current position.

When a node enters discovery state, its T_d timer will be initialized and begin countdown and it enters the first stage. In the first stage, the node will determine whether there exists a leader for its primary residing-group. When the T_d timer reaches zero but the node has not received higher-priority beacon from other nodes with the same working-for group, the node in the unshared grid will enter active state while the node in the shared grid will enter the second stage. Otherwise, i.e., a higher-priority beacon was received from other node with the same working-for group before the T_d timer has reached zero, the node sets its T_s to be a random value between *enat/2* and *enat* and then enters sleeping state. The node's fastest moving speed *s* and minimal group distance *G* can be used to estimate the node's expected node Group time (*enGt*). If the preset T_s is greater than *enGt*, then T_s will be set to *enGt*.

In the first stage, the node will determine whether there exists a leader for its secondary residing-group. When the T_d timer reaches zero but the node has not received higher-priority beacon from other nodes with he same working-for group, the node will enter active state. Otherwise, the node enters sleeping state. At the beginning of active state, T_a will be set to *enat*. To avoid thrashing, we also set a threshold similar to GAF (such as 30 seconds) to avoid threshing. When the *enat* value is smaller than the threshold, T_a will be set to *enlt*.

When the node becomes active, its T_a timer will execute a countdown after every working period and it will check for whether its power is exhausted. If a node has exhausted its power, we will close this node and change it to the irreversible drop state. If a higher-priority active beacon was received from other node with the same working-for group before the T_a timer has reached zero, the node enters sleeping state. If neither of the above scenarios happened until the T_a timer countdowns to zero, i.e., the node has completed its responsible interval, it will reset its T_d timer and will enter discovery state. After a node has entered sleeping state, it will start countdown on its T_s timer until it reaches zero. When the T_s timer counts down to zero, the node will reset the T_d timer and change its state to discovery state.

3.2 HEC-enh Algorithm

HEC-enh and HEC-bas differ in their discovery and active states. In the HEC-enh discovery state, before the T_d timer reaching zero, if a node receives a beacon from other node in the same group with 0 priority or it receives beacons from nodes with non-0 priority of its two residing group, then it means that the groups in which the node resides already have a leader each.

If all residing groups of a node have leaders, the take-over procedure is executed. If one node's *enlt* is *K* times larger than the *enlt* of the leader, it means that the current leader's power is lower than that of this one. Then, the node sets its T_a to *enat*, broadcasts the active beacon and then enters active state, i.e., the node will take over this group. At the beginning of take-over, the group will have two leaders. The original leader will hear the beacon from the new leader and its state will be changed to sleeping due to its shorter *enlt*. The remaining process is identical to HEC-bas.

4. ANALYSIS

How long can GAF and HEC extend network lifetime compared with pure AODV? Assumed that *n* nodes are evenly distributed in an area of size *A* and radio propagation range of each node is *R*. From GAF's analysis, the network lifetime of GAF will be extended by at most $(n * R^2 /(5 * A))$ times, compared with pure AODV. Recall that the hexagonal virtual grids of HEC have the side length of $(R/\sqrt{28})$. A hexagonal virtual grid area is $(3\sqrt{3} * R^2 /56)$. Therefore, a cluster area is $(57\sqrt{3} * R^2 /56)$. In a cluster, the seven groups with only one active node each would maintain network connectivity. Therefore, the average group area is $(57\sqrt{3} * R^2 /392)$. The minimum number of HEC groups, *g*, is derived $g = A/(57\sqrt{3} * R^2 /392)$. Because all nodes are evenly distributed, each group would have at most *n/g* nodes, which is equal to $(57\sqrt{3}*n*R^2/(392*A))$ nodes. At best (assuming no HEC overhead), the above formula proves that we can extend the network lifetime by a factor of $(57\sqrt{3}*n*R^2/(392*A))$, compared with pure AODV. For network lifetime, the ratio between GAF and HEC is $(n*R^2/(5*A)):(57\sqrt{3}*n*R^2/(392*A))$, approximately 1:1.25. By above mathematical derivation, we have theoretically proven that, in terms of network lifetime, HEC is 25% more effective than GAF.

5. EXPERIMENTAL SIMULATIONS AND PERFORMANCE EVALUATION

To assess the performance of those algorithms, we used the Berkeley Network Simulator 2 (version 2.28) to perform AODV, GAF, HEC-bas and HEC-enh protocols on a single machine (The VINT, 2004). During the simulation, nodes will move freely according to the Random way-point model (D. B. Johnson et al.1996) in a 1500x300 square meters field. We consider two different node pause times: 0 and 900 seconds. Moving speeds will be evenly distributed between 0~1 m/s and 0~20 m/s (these two types of moving speeds represent the speeds of people and automobiles, respectively). We will separately simulate these different protocols under different pause times and moving speeds.

Traffics were generated by continuous bit rate (CBR). Data packet is of size 512 bytes. Each CBR will send data from its source to its destination periodically. The packet rate is fixed at 20 packets per second for each CBR session. The maximum link bandwidth is 2Mb/s. We model a radio with a nominal range of 250 meters under the Two-ray-ground Propagation model (Kasten, 2001) (Stemm and Katz, 1997:1125-1131) (Broch et al. 1998:85-97).

Figs. 6 and 7 depict the simulation curves of GAF and HEC protocols with x pause time, represented by [GAF, x] or [HEC, x]. Figs. 6 and 7 are the simulation results with moving speed of 0-1m/s (low speed) and 0-20m/s (high speed), respectively. The dotted lines in Figs. 6 and 7 depict the average fractions of survived nodes for varied m's, where m is from 1 to 20. When m is no less than 10, the average fraction of survived nodes tends to be approximately 20%. This means that the network throughput at this time is low. Therefore, effective network lifetime is defined as the interval from the beginning of the simulation to the time when the first instance of 10 failed retransmissions of a packet happens, i.e. the period during which the average fraction of survived nodes is greater than 20%. Simulation results indicate that the network lifetime of HEC is superior to that of GAF under any speed or pause time.

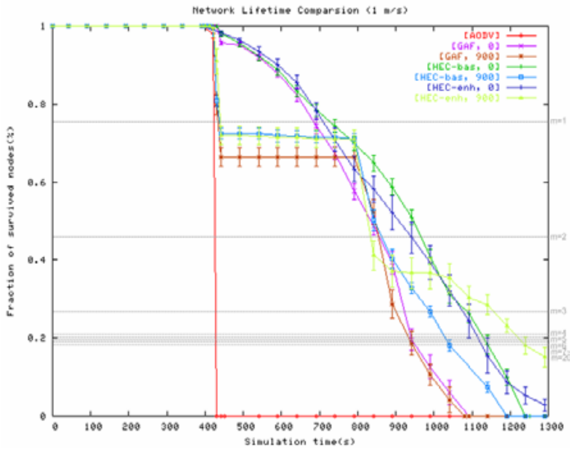

Figure 6. The fraction of survived nodes (0~1 m/s).

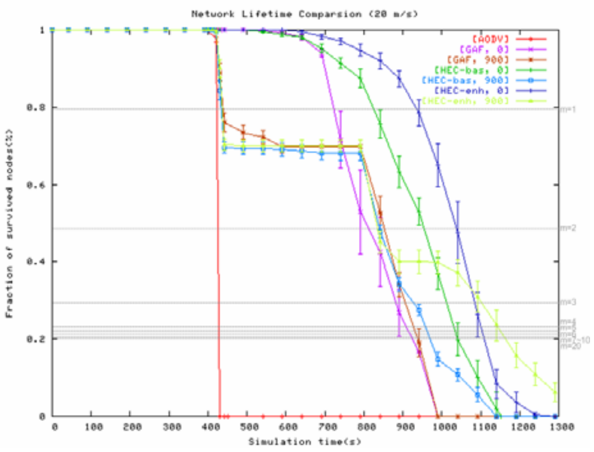

Figure 7. The fraction of survived nodes (0~20 m/s).

At low speed, the effective network lifetimes are approximately 1250 seconds for [HEC-enh, 900], 1150 seconds for [HEC-bas, 0], 1120 seconds for [HEC-enh, 0], 1050 seconds for [HEC-bas, 900], 950 seconds for [GAF, 0], and 930 seconds for [GAF, 900]. HEC-bas and HEC-enh had similar performances under low speed and short pause times, mainly because the T_s of HEC-enh is always set to 47 seconds, and T_s of HEC-bas does not differ greatly from the T_s of HEC-enh. Although HEC-enh employs group take-over mechanism, nodes subject to its average speed move out of the group only once every 47 seconds. Therefore, the performance of HEC-enh is identical to that of HEC-bas.

Under high speed, the effective network lifetimes are approximately 1160 seconds for [HEC-enh, 900], 1120 seconds for [HEC-enh, 0], 1040 seconds for [HEC-bas, 0], 990 seconds for [HEC-bas, 900], 950 seconds for [GAF, 0], and 940 seconds for [GAF, 900]. The group take-over mechanism of HEC-enh allows for electing nodes as active nodes fairly. However, for HEC-bas, electing active nodes without take-over mechanism leads to unfairness. This difference makes HEC-enh able to prolong network lifetime under high speed and short pause time.

In addition, [HEC-bas, 0] performs better than [HEC-bas, 900]. Since the simulation time is only 1300 seconds, longer pause times result in fewer changes to the topology. Therefore, nodes in [HEC-bas, 900] approximately move three times in the entire simulation. This makes node usage in [HEC-bas, 900] extremely uneven. This phenomenon leads to some groups exhausting its nodes quickly, resulting in shortening its network lifetime. Meanwhile, because nodes in [HEC-bas, 0] are with 0 pause time, this will lessen uneven node usage, resulting in longer network lifetime for [HEC-bas, 0]. On the other hand, the HEC-enh protocol performed reversely. Because HEC-enh has take-over mechanism that can allow each group nodes to use energy more evenly, the curve for [HEC-enh, 900] had two stair-like waves in Figs. 6 and 7, while there was only one stair-like wave in [HEC-bas, 900]. This is the reason that [HEC-enh, 900] performed better than [HEC-enh, 0]. The simulation results confirm the analysis that HEC is 25% effective than GAF in extending network lifetime.

6. CONCLUSIONS AND FUTURE WORKS

In this study, we have proposed the HEC protocol for achieving energy efficiency in MANETs. The GAF method partition the network area into many virtual square grids according to the *CDS* concept, while the HEC method uses hexagons to form coverage instead of square grids. From the analysis in Section 4, network lifetime of HEC is 25% higher than that of GAF. Simulations have confirmed our analysis regarding the network lifetime. All in one, the HEC protocol has truly provided an effective and feasible energy efficiency strategy. It is worthy to further investigate the network connectivity of HEC, compared with GAF and AODV.

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