ENERGY-EFFICIENT ADAPTIVE ROUTING FOR AD HOC NETWORKS WITH TIME-VARYING HETEROGENEOUS TRAFFIC

Qing Zhao

Electrical and Computer Engineering
University of California, Davis, CA 95616
qzhao@ece.ucdavis.edu

Lang Tong

Electrical and Computer Engineering
Cornell University, Ithaca, NY 14853
ltong@ece.cornell.edu

ABSTRACT

We propose a hybrid networking strategy for large-scale energy constrained ad hoc networks. Referred to as Energy-Aware GEo-location aided Routing (EAGER), this protocol optimally blends proactive and reactive routing strategies for energy efficiency. Specifically, EAGER partitions the network into cells and performs intra-cell proactive routing and inter-cell reactive routing. The cell size and transmission range are optimized analytically for energy efficiency. Furthermore, by gluing cells around the hot spots in the network, EAGER is capable of adapting to time-varying heterogenous traffic patterns.

1. INTRODUCTION

Routing is one of the fundamental and challenging tasks for large-scale mobile ad hoc networks (MANET). According to whether nodes maintain the locations of others in the network, routing protocols can be categorized into two classes: topology-based and position-based. The defining characteristic of position-based routing protocols is the use of the location information of the destination node [1]. This information can be used to either reduce the overhead associated with route discovery or or forward the message directly toward the destination. In exchange for the reduced route discovery overhead, position-based approach encounters the location service overhead: control messages have to be exchanged among mobile nodes in order to maintain the up-to-date position information.

In this paper, we focus on the topology-based routing approach which does not require a node to maintain the position information of any other nodes. Topology-based routing protocols can be further divided into proactive, reactive, and hybrid approaches. In proactive routing, all links between nodes and routes between source-destination pairs are maintained regardless of the data traffic. Such a strategy avoids the need of finding routes for each message and is especially efficient when the nodes are relatively stationary and traffic relatively heavy. Reactive routing, on the other hand, finds a route only when a message is to be delivered. It avoids the need of frequent link and route updates therefore substantially reduces energy consumption when the traffic load is light or the network mobility is high. Typical characteristics of energy consumption for proactive and reactive strategies are shown in Fig. 1 which naturally suggest a hybrid strategy: reactive at low traffic load and proactive when the traffic load is high. Implementation complexity of such a strategy aside, one would question whether the optimal hybrid networking strategy would simply trace the minimum of the optimal reactive and proactive strategies. If that is the case, simply switching between the two networking protocols leads to the optimal solution. As we shall demonstrate in this paper, simply switching between proactive and reactive strategies leads to suboptimal performance, and there is a substantial gain by pursuing more sophisticated optimal hybrid approach.

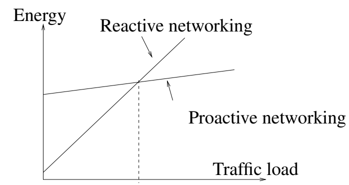

Fig. 1: Energy consumption characteristics.

We propose a hybrid routing protocol which optimally blends proactive and reactive approaches based on the traffic and mobility conditions. Referred to as Energy Aware GEo-location aided Routing (EAGER), this protocol partitions the network into disjoint and equal-sized cells and performs intra-cell proactive routing and inter-cell reactive routing. The design of the intra-cell and inter-cell routing schemes fully utilizes the cell structure of EAGER, resulting in a substantial reduction in overhead and overall energy consumption. The cell size and transmission range are optimized analytically for energy efficiency. Furthermore, by gluing cells around the hot spots in the network, EAGER is capable of adapting to time-varying heterogenous traffic patterns while maintaining energy efficiency.

EAGER employs the hybrid routing principle, namely locally proactive and globally reactive, which was first proposed by Haas and Pearlman [2] in the zone routing protocol (ZRP). Different from ZRP in which each node has its own proactive zone and zones of neighboring nodes are heavily overlapped, EAGER relies on self-location information to partition the network into disjoint proactive cells. The structure of disjoint cells significantly reduces the percentage of nodes involved in a route discovery process. Furthermore, the optimal cell size and transmission range are obtained analytically in EAGER while simulations are resorted to in ZRP to obtain the zone radius. The performance measure used in EAGER also differs from that of ZRP, the former being energy efficiency and the latter routing overhead.

2. THE PROBLEM STATEMENT

We consider a network with N nodes randomly distributed in a disk of radius R. The node distribution is assumed to be uniform with density $\rho = \frac{N}{2\pi R^2}$. Nodes are half duplex and capable of adjusting the transmission power to cover a neighborhood of radius r. Due to node mobility, the state (whether two nodes are within the transmission range of each other) of communication links varies randomly and asynchronously. We assume homogeneous node mobility and parameterize it by λ_n, the average number of changes in the neighbor set experienced by a node in one unit time. The message arrival

This work was supported in part by the Multidisciplinary University Research Initiative (MURI) under the Office of Naval Research Contract N00014-00-1-0564, Army Research Laboratory CTA on Communication and Networks under Grant DAAD19-01-2-0011.

process at each node is stationary with mean λ_m which is referred to as the message duty cycle. Each message contains B_M data bits.

When there is no on-going transmission, nodes are in the sleep state by turning off its transceiver. A wake-up scheme is thus required to bring nodes to the active communication state when necessary. One approach is to wake up nodes by the RF signals, which can be achieved by equipping each node with an energy detector. In this case, nodes cannot be woken up individually; every node within the range r of the transmitting node will be woken up and check whether it is the intended receiver.

A perfect wake-up scheme would be one that brings only the intended receiver back to the active state, thus eliminating unnecessary energy consumption in listening. One possible scheme is to implement a global schedule; nodes are woken up by their internal clock when scheduled for transmission or reception. Another approach is to equip each node with a low power device such as the remotely activated switch (RAS) [3] enabled by the technology of RF tags. When the RAS receives a correct paging sequence (for example, a predetermined function of the node ID), it turns on the transceiver and brings the node to the active state. In this paper, we focus on the case where perfect wake-up is enabled by the use of paging. We point out that the proposed hybrid routing protocol can be extended to incorporate different wake-up schemes.

3. HYBRID NETWORKING: EAGER

The basic idea of EAGER is to partition the network into equal-sized cells. Routes within a cell are maintained proactively while routes across cells are established reactively. By adjusting the cell size according to the message duty cycle λ_m and network mobility λ_n, energy efficiency better than both proactive and reactive networking can be obtained. Below, we give details of EAGER by specifying the network partition, the route discovery, and the parameter optimization.

3.1. Network Partition

As shown in Figure 2, the network is partitioned into cells; each cell is a hexagon with radius c_r which is chosen optimally. This partition is predetermined and known to all nodes. We assume that every node is equipped with GPS thus aware of the cell it is located in. Each cell has a preassigned paging sequence known to all nodes (for example, the paging sequence of a cell can be a predetermined function of the cell location). Thus, a node can be woken up by either its own paging sequence or the paging sequence of its cell. We need total 7 paging sequences to ensure that any two adjacent cells do not share the same paging sequence.

3.2. Route Discovery

3.2.1. Intra-Cell Proactive Routing

Each one-hop transmission between two nodes in the same cell has a range of r_I which is optimized for energy efficiency (see Section 3.3). Routes between any pair of nodes within a cell is obtained proactively. Nodes within a cell are partitioned into two groups: inner nodes and periphery nodes. Roughly speaking, periphery nodes are responsible for relaying packets across cell boundaries. Specific definition of periphery nodes will be given in Section VI-B.2. Based on its own location, a node can determine whether it is a perphery node. A flag indicating periphery nodes is included in the link-state update packets so that a node has the knowledge of all periphery nodes in its cell. We consider here the standard link state routing although other proactive routing protocols may be used.

3.2.2. Inter-Cell Reactive Routing

When node A has a message for node Z, it first checks whether Z is in the same cell. If so, the message can be transmitted immediately to Z using the in-cell route that has been established proactively. Otherwise, A initiates route discovery by flooding a request message containing the addresses of A and Z. The cell structure of EAGER can be efficiently utilized to reduce the overhead associated with inter-cell route discovery. Specifically, based on the cell structure, we can ensure that the traffic flow of a route discovery request is always directed toward unknown territory and visits each cell at most once, thus eliminating redundant communications of the request packets. We illustrate the traffic flow of request packets

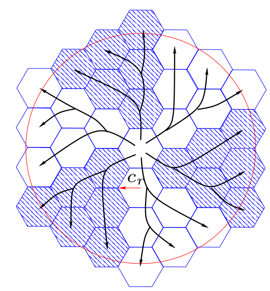

Fig. 2: Traffic flow of a route discovery request.

resulted from one possible implementation of EAGER in Figure 2 where, without loss of generality, we assume the source is located in the center cell of the network. As seen from Figure 2, the flooding of the route discovery request is along the radial direction with respect to the cell of the source and the traffic flow passes a cell at most once. Furthermore, the communications between two neighboring cells are carried through nodes located in the peripheral area (indicated by shaded trapezoids in Fig 4). In EAGER, the size of the peripheral area is chosen optimally to minimize the number of nodes involved in the route discovery.

To present the inter-cell reactive routing scheme in detail, we need the definition of *level* that describes the distance between two cells, the notion of *adjacency* to specify the direction of traffic flow, and the concept of *periphery* for nodes that locate near the boundary of a cell.

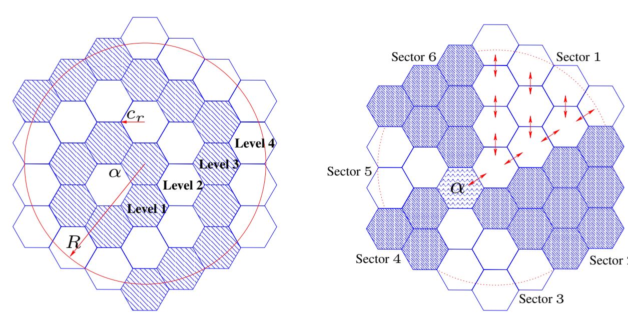

Fig. 3: Cell structure of EAGER: level and adjacency.

Definition 1 *Let α be the cell of the source. The network is partitioned into rings of cells around α. (See Fig. 3-Left). The level of a cell with respect to α is the level of the ring to which the cell belongs.*

Level is a measure of the distance between two cells. As shown in Figure 3-Left, cells in the first and third levels w.r.t. α are shaded.

The definition of adjacent cell helps to ensure that a route discovery request visits a cell at most once. One possible definition is as follows. Treat the source cell α as the center of the network and partition all cells into six sectors as shown in Figure 3-Right where even-numbered sectors are shaded. In each sector, there are exactly i cells on level i provided that i is not the highest level in this sector. Sectors, however, may not contain the same number of cells unless α is indeed the geographic center. We then define adjacent cells identically and independently for all sectors. In Figure 3-Right, adjacent cells in sector 1 are illustrated by double arrows. There are many equivalent ways of defining adjacent cells. A formal definition is as follows.

Definition 2 *The relation of adjacency w.r.t. cell α satisfies the following conditions.*

1. *It is defined for two cells on two consecutive levels w.r.t. α.*
2. *It is defined for two cells that are geographic neighbors.*
3. *For a cell on level i, there is one and only one adjacent cell on level $i-1$ and at least one adjacent cell on level $i+1$.*
4. *It is symmetric, i.e., if cell β is adjacent to γ, then γ is adjacent to β.*

Finally, we need the notion of *periphery* of a cell. Nodes in the periphery area of a cell are candidates for relaying traffic across the boundary of adjacent cells.

Definition 3 *Let β and γ be two adjacent cells w.r.t. α. The periphery of γ given β, denoted by $\mathcal{P}_{\gamma|\beta}(A_p)$, is an isosceles trapezoid with area A_p that is contained in γ (see Figure 4-left). It satisfies the following conditions.*

1. *Its longer base is the common lateral shared by β and γ.*
2. *Two angles associated with the longer base are 60^o.*

The periphery of γ given β is illustrated in Figure 4-left. The ID of the cell w.r.t. which the adjacent cells are defined can be easily inferred from the context, thus omitted from the notation.

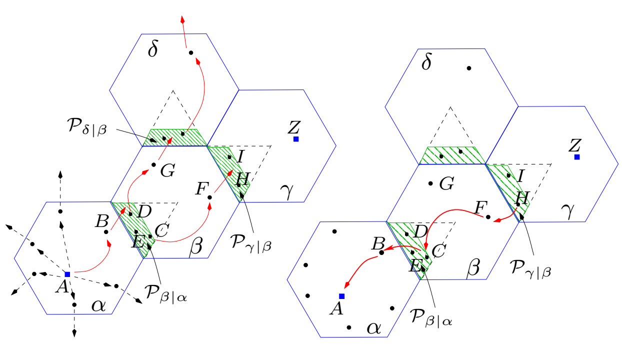

Fig. 4: Inter-cell route discovery.

We are now ready to describe route discovery in EAGER. The basic rule of EAGER is that a node on level i w.r.t. the cell of the source relays the request only to its adjacent cell(s) on level $i+1$ if the destination is not in its cell. This ensures that the propagation of the request is always directed toward the area that has not been searched. Consider the example illustrated in Figure 4-left where we assume the source A is in α and the destination Z is in γ. We consider only the first two levels of sector 1 as shown in Figure 3-right. The procedure is similar in other cells. When A has a message for Z which is not located in the same cell, it chooses a node (say B) in $\mathcal{P}_{\alpha|\beta}$ that is closest (to A) in hop count[1] and transmits a route discovery request containing the addresses of A and Z to this in-cell node B. Node B then replaces A's address with that of its own, adds in the cell ID of α, and broadcasts this request to β using the paging sequence of β. This cross-cell transmission has a range of r_C that is large enough to reach all nodes in $\mathcal{P}_{\beta|\alpha}$. Nodes in $\mathcal{P}_{\beta|\alpha}$ (in our example, they are C, D, and E) set a pointer to B and, after realizing that Z is not in β, propagates the request to their adjacent cells on the next level (γ and δ) as follows. Using the in-cell routing table, each node in $\mathcal{P}_{\beta|\alpha}$ finds out the minimum distance in hop count $d_{\text{min}}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma})$ between $\mathcal{P}_{\beta|\alpha}$ $\mathcal{P}_{\beta|\gamma}$. Let $d(A_1, A_2)$ denote the distance (in hop count) between A_1 and A_2. We define $d_{\text{min}}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma})$ as

$$d_{\text{min}}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma}) \triangleq \min\{d(A_1, A_2), \forall A_1 \in \mathcal{P}_{\beta|\alpha}, A_2 \in \mathcal{P}_{\beta|\gamma}\}.$$

In our example, assume $d_{\text{min}}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma})$ is given by the distance between C and F[2]. Then C transmits the request to F using the in-cell routing table. Similarly, node D propagates the request to G in $\mathcal{P}_{\beta|\delta}$. The request only needs to contain the ID of α and the address of Z. Note that every node in $\mathcal{P}_{\beta|\alpha}$ has the knowledge of the membership of the peripheries and the neighbor sets of all the nodes in the same cell; each node can determine independently whether it needs and to whom to relay the request.

Node F, upon receiving the request from C, adds its own address to the request and broadcasts using the paging sequence of γ. Since the structure of adjacent cells and periphery areas is predetermined, there is no ambiguity to F which adjacent cell on the next level it should transmit to. Similarly, G propagates the requests to δ. Nodes H and I in $\mathcal{P}_{\gamma|\beta}$, after receiving the request, will stop the request transmission and start to reply since the destination Z is in γ. A node in $\mathcal{P}_{\delta|\beta}$, however, continues the propagation of the request to its adjacent cell until the request reaches the highest level.

We now consider the transmission of the reply packet with the help of Figure 4-right. Node H which is closest to Z in hop count among all nodes in $\mathcal{P}_{\gamma|\beta}$ transmits a reply packet containing the ID of α and the addresses of H and Z to node F (from whom the request was received) using the paging sequence of F. Node F then sets a pointer to H, replaces the address of H with its own, and transmits the reply to node C in $\mathcal{P}_{\beta|\alpha}$ that is closest to itself in hop count. Node C then transmits to node B to whom a pointer was set during the transmission of the request. A route between A and Z is thus established.

3.3. Parameter Optimization

In EAGER, three parameters need to be optimized: the cell radius c_r, the periphery size A_p, and the in-cell transmission range r_I. The cross-cell transmission range r_C is determined by A_p; it is the minimum transmission range to fully cover the periphery of size A_p. The criterion we use here is energy efficiency; the parameters of EAGER should be chosen to minimize the total average energy consumption. In general, A_p should be small to minimize the number of nodes involved in the route discovery process, thus reducing

[1] Whether a node is a periphery node and to which periphery area it belongs to are maintained in the in-cell routing table. Note that based on the in-cell routing table which is updated proactively, node A can determine to which node in $\mathcal{P}_{\alpha|\beta}$ the hop count is the smallest.

[2] When a tie accurs, a predetermined function can be used to determined which node(s) to pick from $\mathcal{P}_{\beta|\alpha}$ and/or $\mathcal{P}_{\beta|\gamma}$.

the overhead in energy consumption. However, A_p should be large enough to ensure that there is at least one node in each periphery so that a route discovery request can propagate to every cell if necessary. Specifically, the probability $P_o(c_r, A_p)$ that a request fails to reach every cell should be no larger than p_o, where p_o is the outage probability specified by the network quality-of-service. Let $\mathcal{E}_t(c_r, A_p, r_I)$ denote the total energy consumed by all nodes during the period of $(0, t)$. We have

$$\{c_r^*, A_p^*, r_I^*\} = \arg\min \lim_{t\to\infty} \frac{\mathcal{E}_t(c_r, A_p, r_I)}{t},$$
$$s.t.\ P_o(c_r, A_p) \le p_o,\ r_I \ge r_{\min},$$

where $r_{\min}$ is the minimum transmission range to ensure network connectivity under the hardware constraint [4, 5]. We point out that the cell size c_r can be 0 when the message duty cycle is low. In this case, EAGER becomes a pure reactive protocol. When $c_r = R$, EAGER is a pure proactive protocol. Obtaining the optimal parameters requires the analysis of the energy consumption of EAGER, which can be found in [6]. Using standard link state routing and AODV as representative protocols, we compare the performance of EAGER with that of the proactive and reactive approaches. Shown in Figure 5 are the analytical results on the overall energy consumption. We consider both uniform traffic pattern (left) and localized traffic pattern (right) where the source-destination distance is exponentially distributed with a mean of H hops. We observe that by optimally adjusting the cell size according to the traffic condition, EAGER achieves up to nearly 2 orders of magnitude of reduction in total energy consumption over the minimum offered by the proactive and reactive networking. For localized traffic, the total energy consumption for proactive and reactive approaches remains almost the same for $H = 6$ and $H = 2$ while EAGER, by adapting to the traffic pattern, achieves better energy efficiency when the traffic becomes more localized.

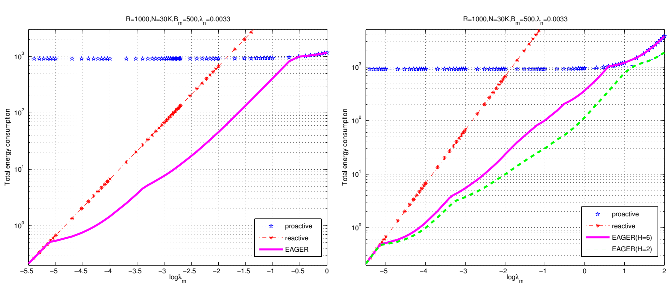

Fig. 5: Comparison of energy consumption.

4. CELL GLUING FOR HETEROGENEOUS TRAFFIC

Crucial to energy-efficient networking is the ability to adapt to the changes in traffic conditions and traffic patterns. Fully utilizing the cell structure, EAGER provides seamless transition across different network operating conditions. Specifically, to adapt to a homogeneous change in the traffic condition (for example, the message duty cycle λ_m of every node increases by the same amount), EAGER optimally adjusts the cell size c_r. When a heterogeneous change in the traffic pattern occurs which creates hot spots or hot routes in the network, EAGER forms proactive zones by gluing cells around the hot spots/routes while maintaining the cell structure for the rest of the network. Cell gluing and de-gluing also allows the handling of heterogeneous QoS. When a task arises which requires timely message delivery to specific geographic locations, cells can be glued together to create a high-rate path that guarantees the specified delay constraint. Once the task is accomplished, cells de-glue and proactive zones resolve; the network returns to an energy saving state.

As illustrated in Figure 6-left, we consider a scenario where a heavy load λ_d of directional traffic needs to be carried across the network. This directional traffic is overlayed on a uniform traffic load of λ_m. As shown in Figure 6, EAGER forms a proactive zone via cell gluing, allowing the tunnelling of the heavy directional traffic across the network. Shown in Figure 6-right is the analytical result on the overall energy consumption as a function of λ_d. We observe that by forming a proactive zone around the hot route created by the directional traffic and keeping the rest of the network in the energy-saving mode, EAGER is capable of maintaining low energy consumption while handling an increasing load of directional traffic. Compared to the pure proactive and reactive strategies, EAGER offers orders of magnitude of reduction in overall energy consumption.

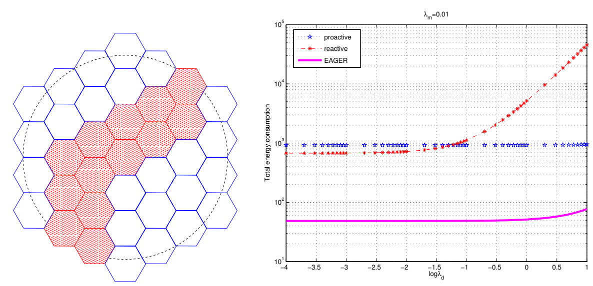

Fig. 6: Comparison of energy consumption.

We point out that cell gluing/degluing are carried out through the periphery nodes (see Figure 4). Specifically, to merge two neighboring cells α and β into one proactive zone, a node in $\mathcal{P}_{\alpha|\beta}$ transmits a request to β and a node in $\mathcal{P}_{\beta|\alpha}$ replies. Once a merge is agreed, nodes in $\mathcal{P}_{\alpha|\beta}$ ($\mathcal{P}_{\beta|\alpha}$) will ensure that the link states of nodes in α (β) propagate to β (α). Thus, routes among nodes in $\alpha \cup \beta$ are maintained; a proactive zone is thus formed. This overhead associated with cell gluing has been taken into account in the result shown in Figure 6. Clearly, the operation of cell gluing/degluing requires the tracking of the traffic condition. We are currently investigating the application of Vapnik-Chervonekis statistical learning theory to the traffic tracking and adaptation. Since all the cross-cell traffic is carried through the peripheral nodes which constitute a small percentage of the network population, the network's capability of adaptive on-line traffic learning is greatly enhanced.

5. REFERENCES

[1] M. Mauve, J. Widmer, and H. Hartenstein, "A survey on position-based routing in mobile ad hoc networks," *IEEE Network*, pp. 30–39, Nov/Dec 2001.

[2] M. Pearlman and Z. Haas, "Determining the optimal configuration for the zone routing protocol," *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 1395–1431, August 1999.

[3] C. Chiasserini and R. Rao, "Combining Paging with Dynamic Power Management," in *Proc. of IEEE INFOCOM*, pp. 996–1004, 2001.

[4] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Trans. Inform. Theory*, vol. 46, pp. 388–404, March 2000.

[5] Q. Zhao and L. Tong, "Energy Efficiency of Large-Scale Wireless Networks: Proactive vs. Reactive Networking." to appear in *IEEE JSAC Special Issue on Advances in Military Wireless Communications*, 2005.

[6] Q. Zhao and L. Tong, "An analytical approach to energy-aware hybrid routing for large-scale mobile ad hoc networks." submitted to *IEEE/ACM Transactions on Networking*, Jan 2005.