Energy-Aware Adaptive Routing for Large-Scale Ad Hoc Networks: Protocol and Performance Analysis

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Abstract—We propose and analyze an energy-aware traffic-adaptive routing strategy for large-scale mobile ad hoc networks (MANETs). Referred to as Energy-Aware GEolocation-aided Routing (EAGER), this protocol optimally blends proactive and reactive strategies for energy efficiency. Specifically, EAGER partitions the network into cells and performs intracell proactive routing and intercell reactive routing. The cell size and the transmission range are optimized analytically. By adjoining cells around hot spots and hot routes in the network, EAGER is capable of handling time-varying and spatially heterogeneous traffic conditions.

Index Terms—Routing protocols, wireless communication, ad hoc networks, energy efficiency.

1 Introduction

Routing is one of the fundamental and challenging tasks for large-scale mobile ad hoc networks (MANETs). 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 [1]. In this paper, we focus on the topology-based routing approach that 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, the network topological information is maintained at every node. Such a strategy avoids the need for establishing routes for each message and is especially efficient when the network topology is relatively static and traffic is relatively heavy. Reactive routing, on the other hand, does not maintain global topological information. When a message arrives, the source floods a request packet over the network, searching for the destination. Such a strategy avoids the need for frequent topological updates and, therefore, substantially reduces energy consumption when the traffic is light or the topological variation is high.

Typical characteristics of energy consumption for proactive and reactive strategies (as shown in Fig. 1) naturally suggest a hybrid approach: reactive at low traffic load and proactive when the traffic load is high. Implementation complexity aside, one would question whether the optimal network configuration is just a simple switch between these two strategies. The problem becomes even more complex when the traffic load and node mobility are time varying and spatially heterogeneous.

Contribution. In this paper, we propose an adaptive routing strategy that optimally blends proactive and reactive approaches based on the traffic load and the rate of topological change. Referred to as Energy-Aware GEolocation-aided Routing (EAGER), this protocol is capable of handling heterogeneous and time-varying traffic conditions.

Illustrated in Fig. 2 is an outline of the proposed routing strategy. We partition the network into cells whose size is optimized according to normal traffic conditions. A node maintains the topological information of its own cells proactively, whereas intercell routes are established reactively. This topological structure allows the handling of both homogeneous and heterogeneous traffic variations. Specifically, adaptation to homogeneous traffic change is achieved by adjusting the cell size. For a heterogeneous traffic pattern, EAGER adjoins neighboring cells to form proactive zones around hot spots and hot routes while the rest of the network remains in a quiescent energy-saving mode (see Fig. 2).

Related Work. Whereas analytical results on energy consumption in large-scale MANETs is scarce, many energy-aware routing protocols have been proposed (see [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], and references therein). In [6], [18], and [19], the energy consumption of several well-known routing protocols are studied and compared via simulations. There is an extensive literature discussing proactive, reactive, and hybrid routing protocols [20], [21], [22], [23]. The energy consumption of such protocols, however, is usually not the primary metric for comparison.

EAGER employs the hybrid routing principle—locally, proactive, and globally reactive—which was first proposed in the zone-routing protocol (ZRP) [24] and later developed in [25], [26], and [27]. Differing from ZRP and its variations, wherein each node has its own proactive zone and zones of neighboring nodes are heavily overlapped,

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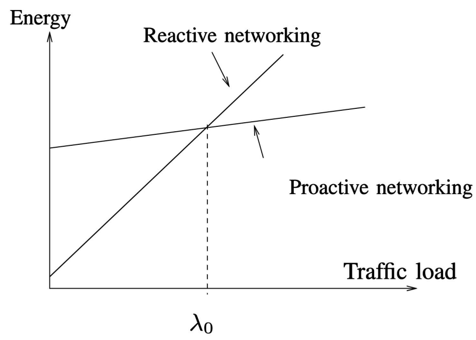


Fig. 1. Energy consumption characteristics: proactive versus reactive networking.

EAGER partitions the network into disjoint proactive cells. This topological structure significantly reduces the number of nodes involved in route discovery and facilitates the handling of heterogeneous traffic via cell combining. Furthermore, the optimal cell size and transmission range are obtained analytically in EAGER, whereas 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 being routing overhead.

For the performance analysis of EAGER, we borrow two basic energy analysis components, the minimum transmission range and the number of hops, from [36] (as stated in Section 4), in which the energy efficiency of classic proactive and reactive routing strategies is analyzed. Given the unique structure of EAGER, however, its energy efficiency analysis is different from that of the proactive and reactive strategies given in [36].

2 The Problem Statement

2.1 The Network Model

As illustrated in Fig. 3, 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 $\rho = \frac{N}{\pi R^2}$. Nodes are half-duplex and capable of adjusting the transmission power to cover a neighborhood of radius r.[1] The rate of topological variation is parameterized by λ_n, which is the rate of neighbor changes experienced by a node. We first consider the uniform traffic pattern with a (per node) message arrival rate of λ_m; that is, a packet generated by a node is equally likely to be intended for any other node in the network. The proposed protocol and its analysis, however, can be easily extended to different traffic patterns as considered in Section 4.3. Each message is assumed to contain B_M data bits.

2.2 The Radio Model

When there is no ongoing transmission, nodes are in the sleep state, with its transceiver turned off. 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 radio frequency (RF) signals, which can be achieved by equipping each node with an energy

1. In our analysis, the transmission range r is optimized for energy efficiency. We do not consider the scenario where the transmission range is selected on a hop-by-hop basis, which requires knowledge of the network topology at each individual node.

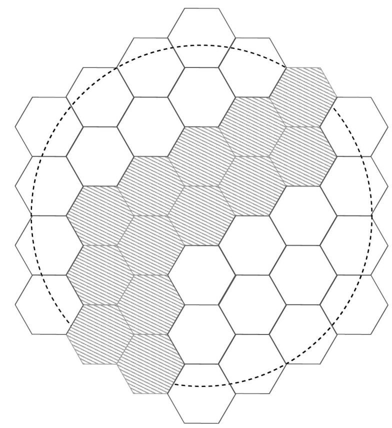


Fig. 2. Adaptation to heterogeneous traffic via cell combining.

detector. In this case, nodes cannot be woken up individually; every node within the range r of the transmitting node will be woken up to 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 they are scheduled for transmission or reception. Another approach is to equip each node with a low power device such as the remotely activated switch (RAS) [28], [29], 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 a perfect wake-up is enabled by the use of paging. Extensions to different wake-up schemes are straightforward.

When a node is receiving, it consumes $E_{\rm rx}$ Joule/bit. A transmission that covers a neighborhood of radius r consumes $E_{\rm tx}(r)$ Joule/bit, which is given in [30] and [38] as follows:

$$E_{\rm tx}(r) = e_{\rm tx} + \max\{e_{\min}, e_{\rm out} r^{\alpha}\}, \tag{1}$$

where α is the path attenuation factor, $e_{\rm tx}$ is the energy consumed by the transmitter circuitry, $e_{\rm out}$ is the antenna

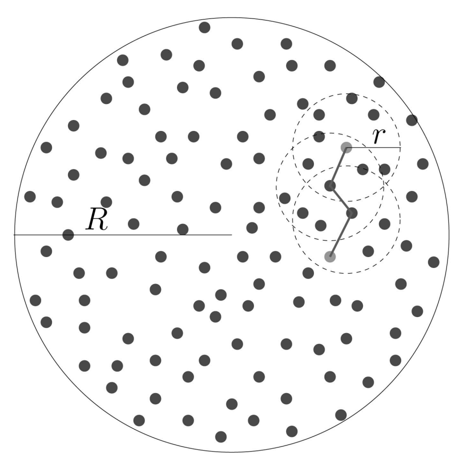


Fig. 3. An ad hoc network with transmission range r.

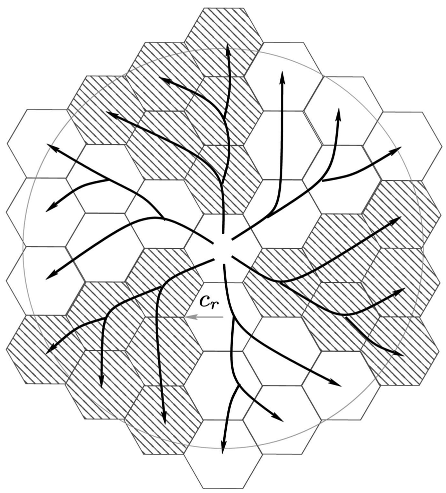


Fig. 4. Traffic flow of a route discovery request (assuming that the source is located in the center cell).

output energy to reach with an acceptable SNR the destination unit distance away, and $e_{\min}$ is the minimum energy radiated regardless of the transmission range.[2] Note that $e_{\min}$ imposes a hard limit on the minimum transmission range:

$$r \geq r_0 \triangleq \left(\frac{e_{\min}}{e_{\text{out}}}\right)^{\frac{1}{\alpha}}. \tag{2}$$

Our goal is to develop an adaptive routing strategy and analyze its energy consumption as a function of the message arrival rate λ_m and topological variation rate λ_n. We focus on the regime of large-scale MANETs; that is, the number of nodes N approaches infinity by increasing either the node density ρ or the network radius R.

3 Energy-Aware Adaptive Routing: The Protocol

The basic idea of EAGER is to partition the network into equal-sized cells according to normal network conditions. Routes within a cell are maintained proactively, whereas routes across cells are established reactively. By adjusting the cell size according to the message arrival rate λ_m and topological variation rate λ_n, energy efficiency better than both proactive and reactive networking can be obtained. Furthermore, the topological structure of EAGER facilitates the adaptation to heterogeneous traffic patterns via cell combining.

3.1 Network Partition

As shown in Fig. 4, the network is partitioned into cells and each cell is a hexagon with radius c_r chosen optimally. This partition is predetermined and known to all nodes. We assume that every node is aware of the cell where it is located through self-localization algorithms [31], [32], [33], [34] or GPS.[3] 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 a total of three paging sequences to ensure that any two adjacent cells do not share the same paging sequence.

3.2 Route Discovery

3.2.1 Intracell Proactive Routing

Each one-hop transmission between two nodes in the same cell has a range of r_I that is optimized for energy efficiency (see Section 3.3). Routes between any pair of nodes within a cell are obtained proactively by using, for example, the standard link-state routing scheme. Nodes within a cell are partitioned into two groups: inner nodes and periphery nodes. Roughly speaking, periphery nodes are located near cell boundaries and are responsible for relaying packets across cells. A specific definition of periphery nodes will be given in Section 3.2.2. Based on its own location, a node can determine whether it is a periphery node. A flag indicating periphery nodes is included in the link-state update packets so that a node has knowledge of all periphery nodes in its cell.

We point out that any proactive scheme can be used for the intracell routing of EAGER. A simple modification is required to ensure that the membership of periphery nodes is maintained at each node.

3.2.2 Intercell 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 by using the in-cell route that has been established proactively. Otherwise, A initiates a 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 intercell 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 (resulted from one possible implementation of EAGER) in Fig. 4 where, without loss of generality, we assume that the source is located in the center cell of the network. As seen from Fig. 4, 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, communications between two neighboring cells are carried through nodes located in the peripheral area (indicated by shaded trapezoids in Fig. 6). 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 intercell 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 located near cell boundaries.

Definition 1. *Let α be the cell of the source. The network is partitioned into rings of cells around α, which defines the level of a cell with respect to α (see Fig. 5a).*

2. The inclusion of a nonzero e_{min} is to account for the fact that the path loss model r^{α} does not apply to small transmission distance r. In other words, even when two nodes are arbitrarily close to each other, a nonzero power level is required to support the communication between them [38].

3. Note that we do not require a node to maintain the location or mobility information of any other nodes. Thus, EAGER belongs to the topology-based approach and differs from the position-based routing protocols [1].

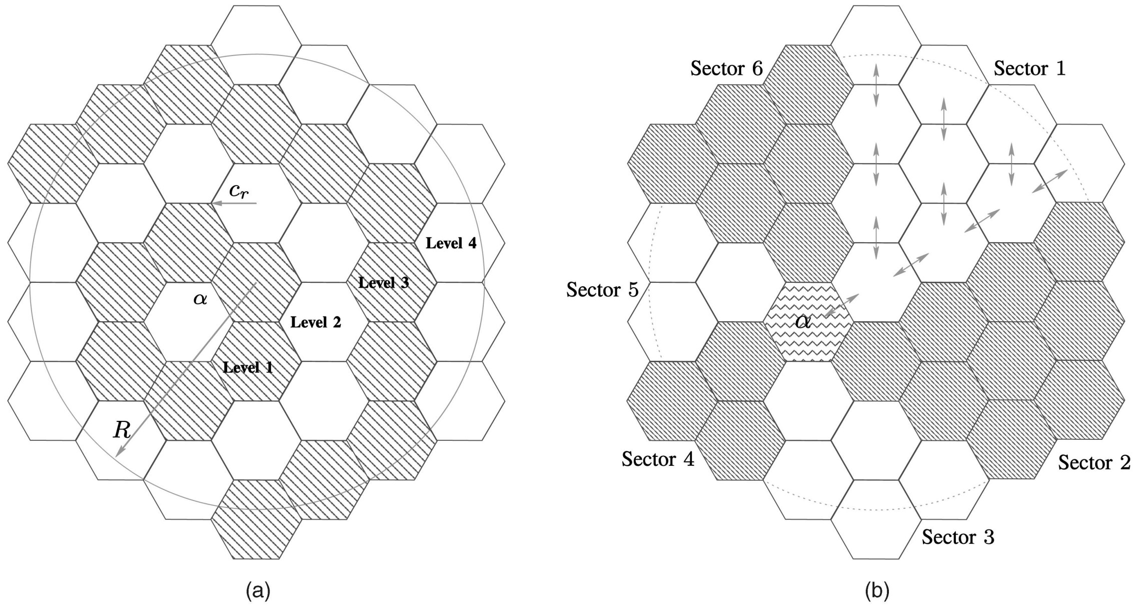


Fig. 5. Cell structure of EAGER. (a) Level and (b) adjacent cells (R: network radius; c_r: cell size; α: source cell).

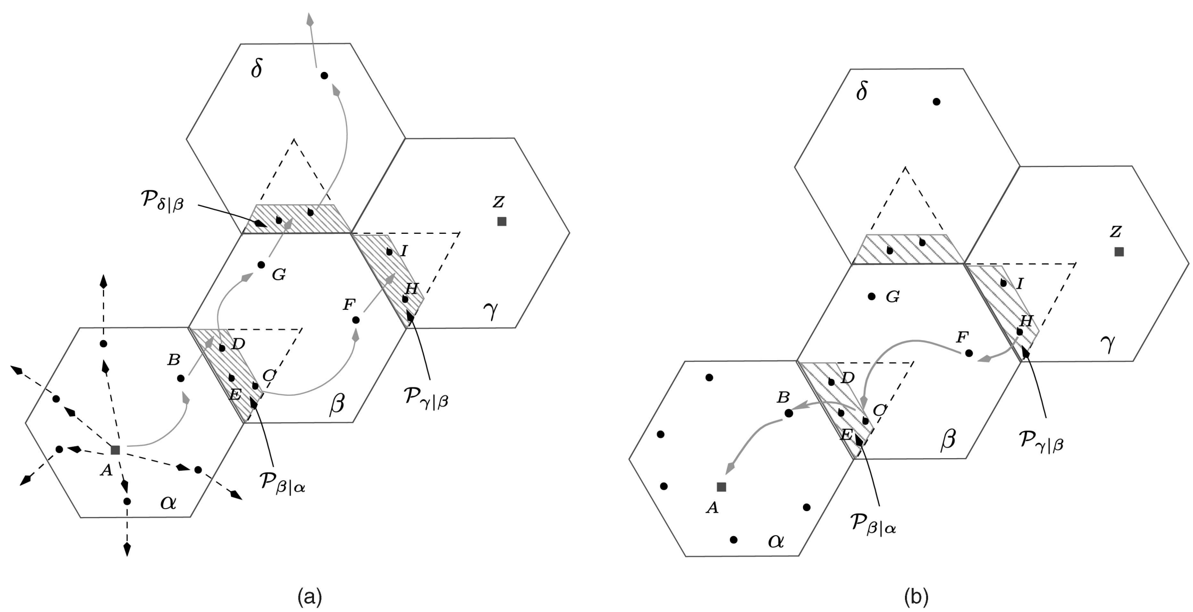


Fig. 6. Intercell route discovery. Transmission of (a) request and (b) reply.

Level is a measure of the distance between two cells. As shown in Fig. 5a, the cells in the first and third levels, with respect to α, are shaded.

The definition of adjacency 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 Fig. 5b, 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 for all sectors. In Fig. 5b, adjacent cells in Sector 1 are illustrated in double arrows. This definition of adjacency defines a tree structure rooted at the source cell α (see Fig. 4, where we assume that the source is located at the center cell).

There are many equivalent ways of defining adjacent cells, provided they satisfy the following properties:

Property 1. *The relation of adjacency with respect to cell α satisfies the following properties:*

- *It is defined for two cells on two consecutive levels with respect to α.*
- *It is defined for two cells that are geographic neighbors.*
- *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 $i+1$.*
- *It is symmetric; that is, if cell β is adjacent to γ, then γ is adjacent to β.*

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

Definition 2. *Let β and γ be two adjacent cells with respect to α. The periphery of γ given β, denoted $\mathcal{P}_{\gamma|\beta}(A_p)$, is an isosceles trapezoid with area A_p that is contained in γ (see Fig. 6a). 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 degrees.*

The periphery of γ given β is illustrated in Fig. 6a. The ID α of the cell with respect to which the adjacent cells are defined can be easily inferred from the context, thus omitted from the notation.

We are now ready to describe route discovery in EAGER. The basic rule of EAGER is that a node in level i with respect to 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 Fig. 6a, where we assume that 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 Fig. 5b. 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 $\mathcal{P}_{\alpha|\beta}$, which is closest (to A) in hop count[4] 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 its own, adds in the cell ID of α, and broadcasts this request to β by 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, propagate the request to their adjacent cells on the next levels (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 $d_{\min}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma})$ between $\mathcal{P}_{\beta|\alpha}$ and $\mathcal{P}_{\beta|\gamma}$. Let $d(A_1, A_2)$ denote the distance (in hop count) between A_1 and A_2. We define $d_{\min}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma})$ as

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

In our example, assume that $d_{\min}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma})$ is given by the distance between C and F.[5] Then, C transmits the request to F by 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 to relay the request and to whom it will be relayed.

Node F, upon receiving the request from C, adds its own address to the request and broadcasts it by using the paging sequence of γ. Since the structure of adjacent cells and periphery areas is predetermined, there is no ambiguity to F as to which 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 Fig. 6b. Node H, which, in hop count, is closest to Z 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) by 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. 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.

We make the following remarks on the intercell route discovery in EAGER:

- With the level structure of EAGER, the propagation of the request is always directed toward the area that has not been searched. Furthermore, a cell on level $i+1$, by the definition of "adjacency," only has one adjacent cell on level i. This ensures that each cell is visited at most once during the search for the destination. The structure of the periphery area can free a large percentage of nodes from unnecessary involvement in route discovery, leading to further overhead reduction.
- The cell partition, the structure of adjacent cells, and the definition of periphery are predetermined and known to all nodes. A node, upon receiving a request from an in-cell node, can determine the cell in which the request will be propagated. Similarly, a node can determine whether it is in the periphery thus possibly responsible for relaying after receiving a request from another cell.
- Level, adjacent cells, and periphery are all defined with respect to the cell of the source. Thus, the cell ID of the source needs to be embedded in all request and reply packets.

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 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 not 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

4. 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 which node in $\mathcal{P}_{\alpha|\beta}$ hop count is the smallest.

5. When a tie occurs, a predetermined function can be used to determine which node should transmit the request.

energy consumed by all nodes during the period of $(0, t)$. We have

$$\{c_r^*, A_p^*, r_I^*\} = \arg\min \lim_{t\to\infty} \frac{\mathcal{E}_t(c_r, A_p, r_I)}{t}, \quad \text{subject to } P_o(c_r, A_p) \le p_o, \ \ r_I \ge r_{\min}, \tag{3}$$

where $r_{\min}$ is the minimum transmission range to ensure network connectivity under the hardware limit given in (2). We point out that the cell size c_r can be 0 when the message duty cycle is low. In this case, EAGER becomes purely reactive. When $c_r = R$, EAGER is purely proactive. In between, we expect better performance than the supreme of proactive and reactive strategies. Obtaining the optimal parameters requires the analysis of the energy consumption of EAGER, which is presented in Section 4.

4 Energy-Aware Adaptive Routing: The Analysis

In this section, we analyze the energy efficiency of EAGER. We start with two basic elements of energy analysis: the minimum transmission range $r_{\min}$ and the number of hops in a minimum energy route.

4.1 Elements of Energy Analysis

4.1.1 The Minimum Transmission Range

The first constraint on the transmission range r is the hardware limit given in (2). The second constraint is network connectivity: r should be large enough so that the network is connected with high probability. Let $r_c(N)$ denote the minimum transmission range to ensure connectivity with probability 1 for a network with N uniformly distributed nodes. We have, from [35] and [39],

$$r \ge r_c(N) \overset{N\to\infty}{\to} R\sqrt{\frac{\log N}{N}} = \begin{cases} \mathcal{O}\left(\sqrt{\frac{\log N}{N}}\right) & \rho \uparrow \\ \mathcal{O}(\sqrt{\log N}) & R \uparrow . \end{cases} \tag{4}$$

We see that, when the network size N is increased by increasing the node density ρ, the minimum transmission range $r_c(N)$ eventually goes to 0. If, however, N is increased by increasing the geographic size R, the transmission range has to grow to infinity with rate $\sqrt{\log N}$ to ensure network connectivity. By combining (2) and (4), we obtain the minimum transmission range $r_{\min}$ for large networks as

$$r \ge r_{\min} \triangleq \max\left\{r_0, R\sqrt{\frac{\log N}{N}}\right\}. \tag{5}$$

4.1.2 The Number of Hops

Let $h(x, r)$ be the number of hops in a minimum energy route for a transmission range r and a source-destination pair with distance x. Clearly, $h(x, r)$ is a random variable depending on the random node locations. When N is large, however, we can give a probabilistic characterization on $h(x, r)$ as shown in the following proposition:

Proposition 1. *For $r \ge r_{\min}$, the number of hops $h(x, r)$ in a minimum energy route converges to $\lceil x/r \rceil$ in probability as $N \to \infty$ by increasing either the network geographic size R or the node density ρ.*

Although the proof of Proposition 1 is technical (see [36]), the intuition behind this proposition is clear, especially when R is fixed and the density ρ increases to infinity. In this case, the probability of finding a set of nodes arbitrarily close to the line connecting the source and the destination approaches 1. When ρ is fixed and R approaches infinity, the minimum transmission range r has to increase at the rate of $\sqrt{\log N}$ to ensure network connectivity (see (4)). Hence, the number of neighbors of each node increases to infinity. The same conclusion is reached as in the case of increasing ρ.

With Proposition 1, we can then study the energy consumption in large networks by using $\lceil x/r \rceil$ as the number of hops. We point out that the characterization of hop counts given in Proposition 1 does not necessarily require the network to be dense; it also holds for networks deployed over large geographic areas.

4.2 Energy Efficiency of EAGER

The energy consumption of EAGER comes from in-cell proactive routing, cross-cell reactive routing, and message transmission.[6] Before calculating the energy consumption associated with each component, we introduce the following notations.

Let $M(c_r)$ denote the number of cells to tile the network when each cell has radius c_r. Let $L(c_r)$ be the number of levels with respect to the cell at the geographic center of the network. For simplicity, we omit (c_r) from the notations for the rest of the paper. Let B_N, B_C, and B_P denote, respectively, the number of bits for a node address, a cell ID, and a paging sequence. We have

$$B_N = \lceil \log N \rceil, \quad B_C = \lceil \log M \rceil, \quad B_P = \lceil \log(N+3) \rceil.$$

4.2.1 In-Cell Proactive Routing

We consider the standard link-state routing scheme. Specifically, each node periodically broadcasts a "hello" message (for example, its own ID) to its neighbors. Every node uses this "hello" message to maintain its neighbor set (the IDs of all the nodes within its transmission range r). Once a node detects a change in its neighbor set, it floods the new neighbor set over its cell. The only difference in the standard link-state routing scheme is that the nodes located in a periphery area need to flood the ID of the cell to which they are adjacent. Assume that the "hello" message is transmitted at the rate (λ_n) of the topological change. We obtain the total energy consumed in in-cell proactive routing in one unit time as

$$\begin{aligned} \mathcal{E}_{\text{HN,I}}(r_I) = {} & N\lambda_n\{B_N(E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) + B_P E_{\text{tx}}(r)\} \\ & + \frac{N^2}{M}\lambda_n\Big\{(B_N + B_C)\frac{r^2}{R^2}(N-1) \\ & (E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) + B_P E_{\text{tx}}(r)\Big\}, \end{aligned} \tag{6}$$

6. To simplify the analysis, we do not consider cache and local route repair.

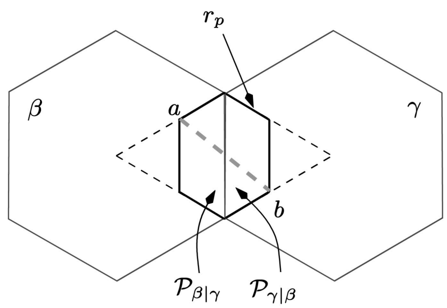


Fig. 7. The size of periphery.

where the first term is the energy consumed in the transmission of "hello" messages: B_N is the length of the message and every "hello" message is decoded by all the neighboring nodes. The second term is the energy consumed in the flooding of neighbor sets: $B_N \frac{r^2}{R^2}(N-1)$ is the average number of bits to represent the neighbor set; each node floods, on the average, λ_n times per unit time, where each flood consists of N transmissions and every transmission is decoded by all the neighbors. The paging sequence of the cell is used in these transmissions.[7]

4.2.2 Cross-Cell Reactive Routing

When node A in cell α has a message for Z, with probability $1 - 1/M$, Z is in a different cell. In this case, a route needs to be established before the message transmission. We divide the energy consumed in the reactive route discovery into four components and calculate them separately as follows.

Initiation. To initiate a route discovery, A transmits a request packet containing the addresses of A and Z to six nodes located in the six periphery areas of α (see Fig. 6a). These transmissions use the in-cell routes that have been established. Node-paging sequences are used to activate nodes on the routes for relay. The energy consumed in this step is given by

$$\mathcal{E}_{\text{HN,C1}} = 6\{2B_N(E_{\text{tx}}(r_I) + E_{\text{rx}}) + B_P E_{\text{tx}}(r_I)\}\bar{h}_I, \qquad (7)$$

where $\bar{h}_I = \lceil \frac{2c_r}{r_I} \rceil$ gives an upper bound on the number of hops for in-cell transmission when the network size N is large (see Proposition 1).

Propagation of request to adjacent cells. The second component in route discovery is to propagate the request to adjacent cells. See, for example, the transmission of B to cover $\mathcal{P}_{\beta|\alpha}$ and the transmission of F to cover $\mathcal{P}_{\gamma|\beta}$ in Fig. 6a. These transmissions have a range of r_C and use the paging sequences of corresponding adjacent cells. The energy consumption here depends on the size A_p of the periphery, which determines the number of listening nodes and the cross-cell transmission range r_C. For energy efficiency, A_p should take the minimum value $\underline{A_p}$ allowed by the outage probability p_o as calculated below.

Consider the propagation of request from cell β to γ, as shown in Fig. 7. One route discovery involves the total $2(M-1)$ periphery areas, half of which contain nodes for receiving the request from a lower level and the other half of which for transmitting the request to the next level. To ensure that the request can reach every cell, there should be at least one node in each of these $2(M-1)$ periphery areas. As shown in [39], the topological difference between a network with N uniformly distributed nodes and a 2D Poisson distributed network with the same density ρ is negligible when N is large. We thus have

$$\begin{aligned} &(1 - e^{-A_p \rho})^{2(M-1)} \geq 1 - p_o, \\ &i.e., \quad A_p \geq \underline{A_p} \triangleq -\frac{1}{\rho}\log\Big(1 - (1-p_o)^{\frac{1}{2(M-1)}}\Big). \end{aligned} \qquad (8)$$

To ensure that the transmission from a node randomly located in $\mathcal{P}_{\beta|\gamma}$ can fully cover $\mathcal{P}_{\gamma|\beta}$, the transmission range r_C should be equal to the distance between a and b in Fig. 7. We thus have

$$r_C = \sqrt{c_r^2 - 2c_r r_p + 4r_p^2}, \quad \text{with } r_p = c_r - \sqrt{c_r^2 - \frac{4\sqrt{3}}{3}\underline{A_p}}, \qquad (9)$$

where r_p is the minimum length of the sides of the periphery (see Fig. 7).

Let $\bar{A}_p$ denote the maximum area covered by a transmission (with range r_C) from a randomly located node in an adjacent cell. It is easy to show that

$$\bar{A}_p = \begin{cases} c_r r_C + \frac{\sqrt{3}}{3} r_C^2 & \text{if } r_C \leq \frac{\sqrt{3}}{2} c_r \\ A_c(c_r) - (2\sqrt{3}c_r^2 - 3r_C c_r + \frac{\sqrt{3}}{3} r_C^2) & \text{otherwise,} \end{cases} \qquad (10)$$

where $A_c(c_r)$ denotes the area of a cell with radius c_r. The energy consumed in propagating the request to adjacent cells is thus upper bounded by[8]

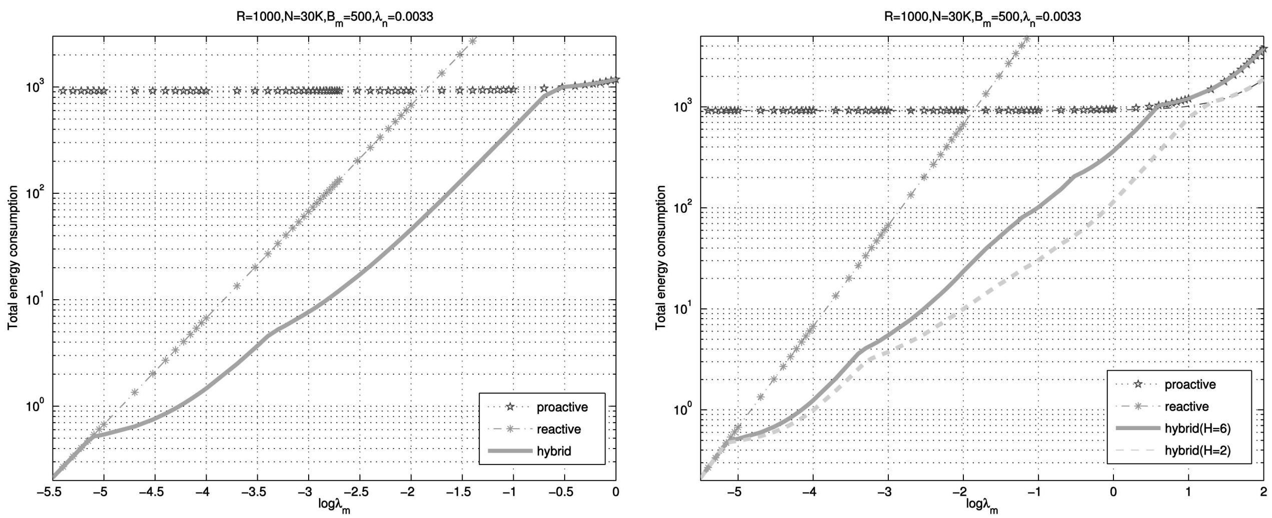
$$\begin{aligned} \mathcal{E}_{\text{HN,C2}} = (M-1)\{&(2B_N + B_C)(E_{\text{tx}}(r_C) + \bar{A}_p \rho E_{\text{rx}}) \\ &+ B_P E_{\text{tx}}(r_C)\}, \end{aligned} \qquad (11)$$

where $M-1$ is the maximum number of cross-cell transmissions during the propagation of the request packets in one route discovery and $2B_N + B_C$ is the number of bits for the source cell ID and the addresses of the transmitting node and the destination. In every transmission, the average number of receiving nodes is upper bounded by $\bar{A}_p\rho$.

In-cell transmission of request. The third component in route discovery is the transmission of the request within a cell for the purpose of propagating the request to the next level. See the transmission from C to F and D to G in Fig. 6a. Clearly, such transmissions are not necessary for the $6L$ cells on the highest level. Considering that the transmission within the source cell has been taken care of in (7), we have

7. The energy consumed by the (passive) RAS in detecting the paging sequence is negligible [28], [29]. Thus, we only consider the energy consumed in the transmission of the paging sequences.

8. It is possible that the minimum value of A_p given in (8) turns out to be larger than $A_c(c_r)/6$ for small c_r (recall that $A_c(c_r)$ denotes the area of a cell). In this case, we can still obtain an upper bound on energy consumption by setting $A_p = A_c(c_r)$ and $r_C = 2\sqrt{3}c_r$; that is, the transmission of a node randomly located in a cell can be heard by all nodes in the adjacent cell. In this case, the number of cell-paging sequences can be larger than 3.



(a) (b)

Fig. 8. Energy consumption of proactive, reactive, and hybrid networking. (a) Uniform traffic. (b) Localized traffic.

$$\begin{aligned}\mathcal{E}_{\text{HN,C3}} = &(M-1-6L)\bar{h}_I\{(2B_N+B_C)(E_{\text{tx}}(r_I)+E_{\text{rx}})\\ &+B_P E_{\text{tx}}(r_I)\},\end{aligned} \tag{12}$$

where $\bar{h}_I = \lceil\frac{2c_r}{r_I}\rceil$ is an upper bound on the number of hops for in-cell transmissions.

Transmission of reply. When the request reaches the cell where the destination is located, reply packets are transmitted back to the source. The number of transmissions that occur during this process depends on the level of the destination with respect to the source cell α. We obtain an upper bound on the total energy consumed in the transmissions of reply as

$$\begin{aligned}\mathcal{E}_{\text{HN,C4}} = &\{(2B_N+B_C)(E_{\text{tx}}(r_I)+E_{\text{rx}})+B_P E_{\text{tx}}(r_I)\}\bar{h}_I\bar{l}_D\\ &+\{(2B_N+B_C)(E_{\text{tx}}(r_C)+E_{\text{rx}})+B_P E_{\text{tx}}(r_C)\}\bar{l}_D,\end{aligned} \tag{13}$$

where $\bar{l}_D = \frac{4L+1}{3}$ is an upper bound on the average level of the destination cell (see [37]). The first term in (13) is the energy consumption for in-cell transmission with a range of r_I and the second term is the energy consumption for cross-cell transmission with a range of r_C.

From (7), (11), (12), and (13), we obtain the total energy $\mathcal{E}_{\text{HN,C}}(r_I, A_p)$ consumed in one cross-cell route discovery as

$$\mathcal{E}_{\text{HN,C}} = \left(1-\frac{1}{M}\right)(\mathcal{E}_{\text{HN,C1}}+\mathcal{E}_{\text{HN,C2}}+\mathcal{E}_{\text{HN,C3}}+\mathcal{E}_{\text{HN,C4}}), \tag{14}$$

where $1-\frac{1}{M}$ is the probability that the source and the destination are not in the same cell thus requiring intercell reactive routing.

4.2.3 Message Transmission

After the route is established, the message is transmitted from the source to the destination. The transmission contains $2B_N + B_P + B_M$ bits, where $2B_N$ is for the addresses of the source and the destination, B_P is for the paging sequences activating nodes on the route, and B_M is for the message length. Similar to the analysis of the energy consumption in the transmissions of route reply (see (13)), we obtain an upper bound on the energy consumed in the transmission of one message:

$$\begin{aligned}\mathcal{E}_{\text{HN,M}} = &\{(2B_N+B_M)(E_{\text{tx}}(r_I)+E_{\text{rx}})+B_P E_{\text{tx}}(r_I)\}\bar{h}_I\bar{l}_D\\ &+\{(2B_N+B_M)(E_{\text{tx}}(r_C)+E_{\text{rx}})+B_P E_{\text{tx}}(r_C)\}\bar{l}_D.\end{aligned} \tag{15}$$

We now compute the total energy consumed in one time unit where, on the average, $\lambda_m N$ messages and, thus, route discovery processes are generated. We have

$$\mathcal{E}_{\text{HN}} = \min_{c_r, A_p, r_I}(\mathcal{E}_{\text{HN,I}} + \lambda_m N\mathcal{E}_{\text{HN,C}} + \lambda_m N\mathcal{E}_{\text{HN,M}}), \tag{16}$$

where $\mathcal{E}_{\text{HN,I}}$, $\mathcal{E}_{\text{HN,C}}$, and $\mathcal{E}_{\text{HN,M}}$ are given in (6), (14), and (15), respectively. The above optimization can be done numerically.

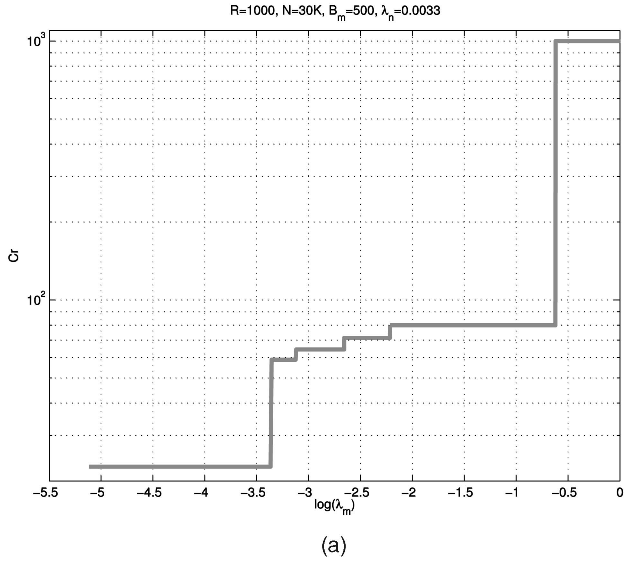
4.3 Numerical Examples

4.3.1 Comparison of Energy Efficiency

We now evaluate the energy efficiency of EAGER as compared to the proactive and reactive strategies. The performance of EAGER is obtained using the analysis given in Section 4.2. We use the analysis of proactive (based on the standard link-state routing) and reactive (based on AODV) strategies developed in [36].

We consider a large network with 30,000 nodes randomly distributed on a disk with radius $R = 1{,}000$ m. The outage probability p_o is set to 0.01. We use typical values for the radio model given in [30] and set $e_{min} = e_{out}$.

Shown in Fig. 8 are the analytical results on the total energy consumption as a function of the message arrival rate λ_m. In Fig. 8a, we consider a uniform traffic pattern. We observe that, at a low message arrival rate, EAGER converges to a pure reactive scheme; that is, the cell radius c_r goes to 0. When the message arrival rate is high, EAGER converges to a pure proactive scheme; the cell radius approaches R (see Fig. 9). When the message arrival rate is in the range of $[10^{-5}, 10^{-0.5}]$, EAGER provides up to two orders of magnitude of reduction in



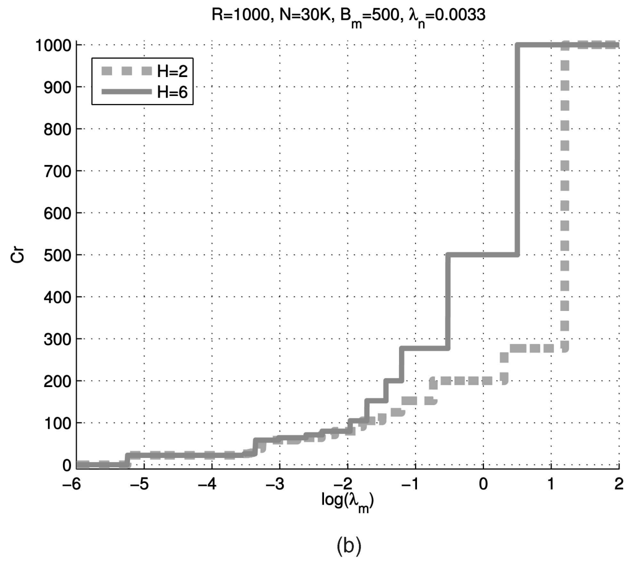


Fig. 9. Impact of traffic load on the optimal cell size (s) Uniform traffic. (b) Localized traffic.

total energy consumption over the minimum offered by the proactive and reactive strategies.[9]

Shown in Fig. 8b is the comparison of energy consumption under a localized traffic pattern. In this case, the source-destination distance measured in hops is geometrically distributed with mean H. For proactive and reactive strategies, the total energy consumption remains almost the same for $H = 6$ and $H = 2$. By optimally choosing the cell size c_r according to the traffic pattern, however, EAGER achieves better energy efficiency when the traffic becomes more localized.

The performance comparison between EAGER and the standard proactive and reactive approaches should be understood in a proper context. The performance gain achieved by EAGER results from its optimal combining of proactive and reactive strategies as well as its use of self-location information. Results obtained in this paper suggest the possibility and the potential gain of utilizing self-location information in a topology-based routing approach.

4.3.2 Monotonicity of Optimal Cell Size

Based on the performance analysis of EAGER, we demonstrate the monotonicity of the optimal cell size c_r^* with respect to the traffic load λ_m and mobility rate λ_n. In Fig. 9, we study the impact of λ_m on the optimal cell size c_r^* for both uniform and localized traffic patterns. These results show that c_r^* increases monotonically with λ_m, indicating that the network should be more proactive when the traffic is heavy. Furthermore, for localized traffic, a smaller average distance between source and destination leads to a smaller c_r^*.

Fig. 10 illustrates the impact of mobility rate λ_n on c_r^*. For both uniform and localized traffic, the optimal cell size c_r^* monotonically decreases with λ_n, indicating that the network should be more reactive when the mobility is high.

These results confirm our intuition. We point out that, in the parameter optimization of EAGER, we consider only cell sizes that lead to an exact coverage of the network (see Fig. 5). As a consequence, c_r takes a finite number of possible values, which simplifies the optimization.

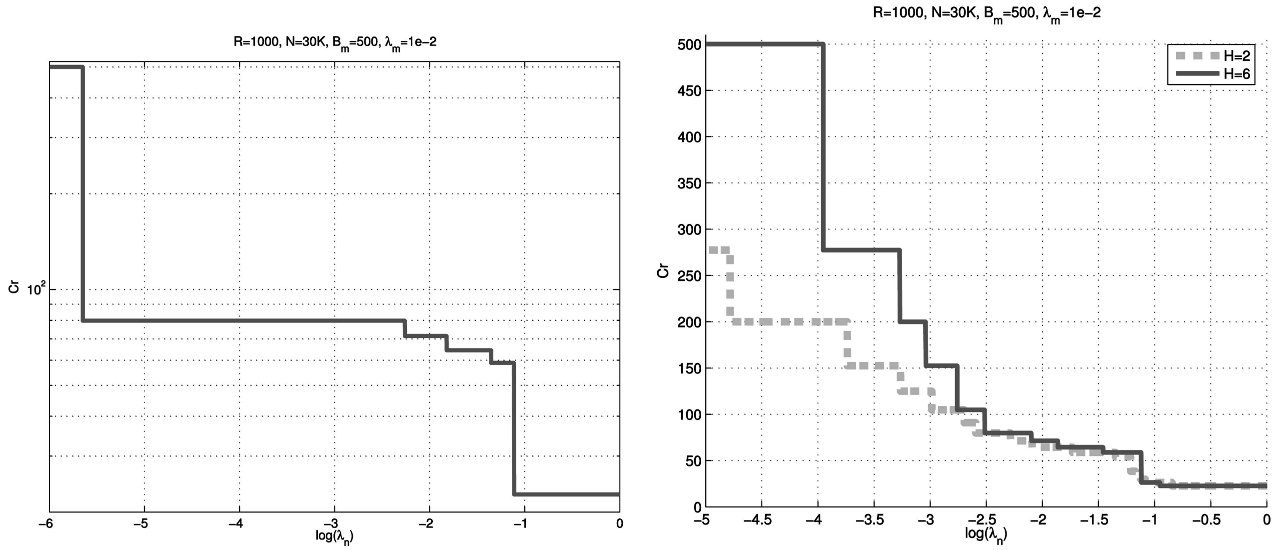
4.3.3 Robustness of EAGER to Mismatched Network Parameters

Figs. 9 and 10 indicate that a particular cell size is optimal for a range of traffic load λ_m and mobility rate λ_n. It thus follows that errors in λ_m or λ_n do not necessarily result in performance loss. The numerical examples given in Fig. 11 demonstrate the robustness of EAGER to estimation errors in λ_m. We observe that, even when the relative error in λ_m is up to 80 percent, the performance loss of EAGER is within 11 percent for both localized and uniform traffic patterns. Similar results have been observed for estimation errors in λ_n.

5 Cell Combining for Heterogeneous Traffic

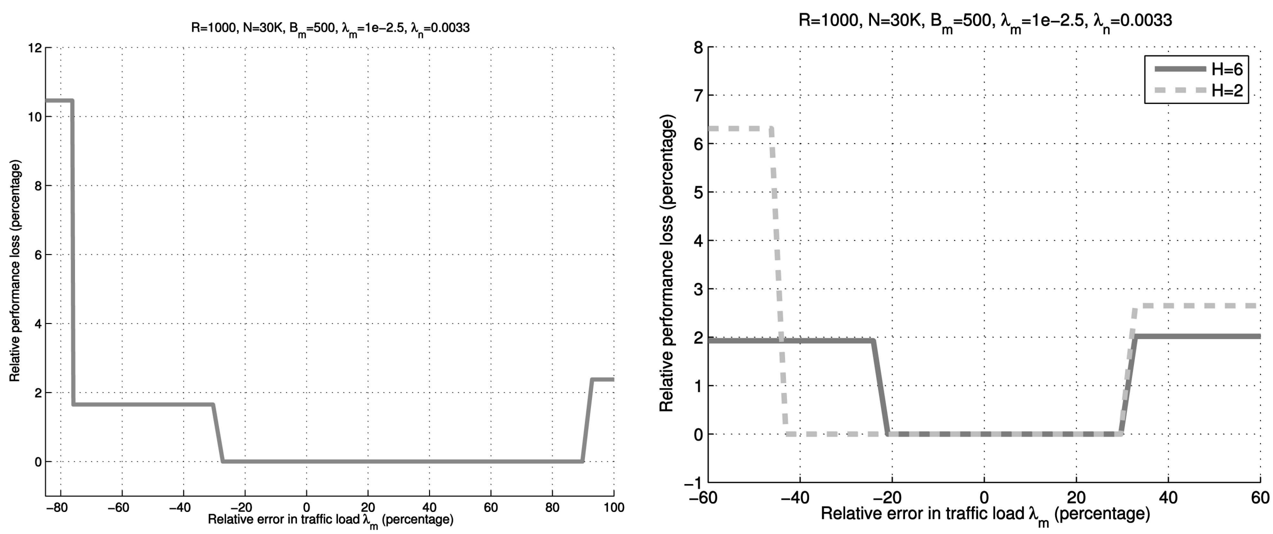
Crucial to energy-efficient networking is the ability to adapt to the changes in traffic conditions and traffic patterns. By fully utilizing the cell structure, EAGER provides a seamless transition across different network operating conditions. Specifically, to adapt to a homogeneous change in the traffic 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 adjoining

9. We provide here a heuristic explanation for the performance improvement achieved by EAGER under uniform traffic. As we have shown in [36], when the network size N increases while the network radius R is fixed, the total energy consumption of proactive routing is dominated by the global flooding of the updated topological information. For a fixed traffic load λ_m and mobility rate λ_n, this overhead scales with N as $\mathcal{O}(N^4 \log N)$. For reactive routing, the dominating factor is the flooding of route discovery request, which scales as $\mathcal{O}(N^3 \log N)$. For EAGER, if we partition the network into M cells, the energy consumption of the proactive component is given by $\mathcal{O}(\frac{N^4}{M^3}\log\frac{N}{M})$ (consider M networks each with size $\frac{N}{M}$), which decreases with M. The energy consumption of the reactive component, however, increases with M at $\mathcal{O}(M^3 \log M)$ (consider each cell as a node since topology within each cell is known). The total energy consumption of EAGER can be considered as a linear combination of these two, with coefficients determined by λ_m and λ_n. By optimally choosing the number M of cells (that is, cell size c_r), EAGER leads to significant energy reduction even for uniform traffic. A similar explanation can be obtained if we consider that N is increased by increasing R.



(a) (b)

Fig. 10. Impact of mobility rate on the optimal cell size. (a) Uniform traffic. (b) Localized traffic.



(a) (b)

Fig. 11. Impact of estimation errors in traffic load on the performance of EAGER. (a) Uniform traffic. (b) Localized traffic.

cells around the hot spots and the hot routes while maintaining the cell structure for the rest of the network.

We consider a network whose nominal condition is defined by a uniform traffic, with $\lambda_m = 0.01$. The network is partitioned according to this nominal condition. Overlaid with the uniform traffic is a heavy load λ_d of directional traffic that needs to be carried across the network. Specifically, nodes located within a horizontal band with width of $2c_r$ at the center of the network generate messages (besides the uniform traffic with rate λ_m) for nodes on their right within the band.

As illustrated in Fig. 2, EAGER forms a proactive zone via cell combining, allowing the tunneling of the heavy directional traffic across the network. Shown in Fig. 12 is the analytical result[10] 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 the overall energy consumption.

We point out that cell combining is carried out through the periphery nodes (see Fig. 6). 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 $\alpha(\beta)$ propagate to $\beta(\alpha)$. 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 Fig. 12.

10. The analysis of energy consumption in this case can be similarly obtained by considering separately the uniform traffic and directional traffic.

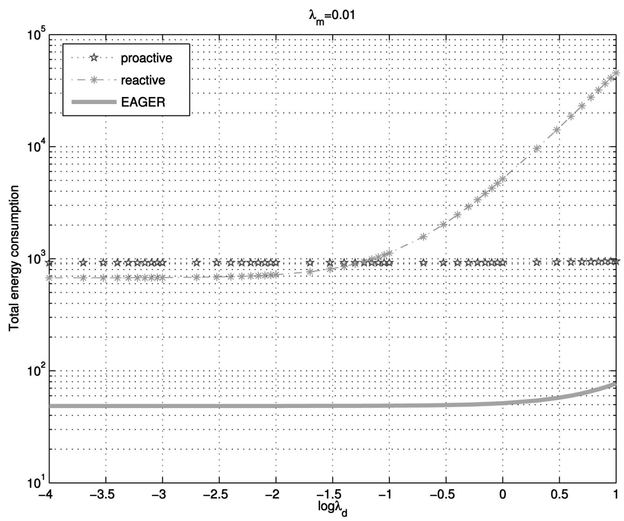


Fig. 12. Energy consumption of proactive, reactive, and hybrid networking: directional traffic.

A critical element of the proposed adaptive routing strategy is a signal processing module that provides timely and accurate traffic estimation and change detection. Under the topological structure of EAGER, traffic estimation and change detection are performed by periphery nodes that observe all the traffic passing through the cell boundaries. We are currently investigating the application of Vapnik-Chervonekis statistical learning theory to traffic estimation and change detection. Since peripheral nodes only constitute a small percentage of the network population, the network's capability of adaptive online traffic learning is greatly enhanced.

Overlaid with the signal processing module for traffic estimation and change detection is a sequential decision making module that decides whether a reconfiguration is justified by comparing the reward and the cost of cell combining. Based on the traffic estimates, peripheral nodes need to decide whether a cell combining process should be initiated. We are currently investigating the use of temporal and spatial traffic statistics for optimal decision making.

6 Conclusion and Future Work

We propose in this paper a traffic-adaptive routing protocol that optimally combines the proactive and reactive strategies. The energy efficiency of the proposed protocol is analyzed in the asymptotic regime. The results presented in this paper are analytical in nature. Idealized assumptions are made, for they are necessary to make the analysis tractable. We aim at revealing the underlying relationships and structures that govern the network behavior instead of matching to specific implementations. The analysis presented here should be viewed as a benchmark with which simulation-based approaches can be cross-checked.

Several directions can be pursued to potentially improve the performance of EAGER. First, EAGER adopts intracell proactive routing. An alternative is to use geographic forwarding for intracell traffic, given that the cell structure, the adjacency relation, and the peripheries are geographically defined. In this case, a different set of analyses is required and the optimal parameters of EAGER will be different. It would be interesting to compare the performance of EAGER based on intracell geographic routing with that based on intracell proactive routing.

Second, the intercell reactive routing is based on a hexagonal network partition, and the flow of route discovery requests follows a tree structure rooted at the source cell. Whether such an intercell routing structure is optimal is a complex problem requiring further investigation. Would network partitions using triangles and squares provide more efficient route discovery? Since, in these cases, route requests propagate in three or four, instead of six, directions, is it possible that a larger percentage of request transmissions can be saved when the destination is found in a particular direction? Furthermore, what is the optimal way to construct the traffic flow of route discovery based on the geographic partition of the network?

Third, the current design of EAGER focuses on energy efficiency; it ensures that a route discovery request visits a cell at most once. This makes EAGER sensitive to failed communications, and the trade-off between energy efficiency and robustness needs to be examined. Acknowledgement and multipath routing can be introduced into EAGER to balance energy efficiency and robustness to failed communications.

Acknowledgments

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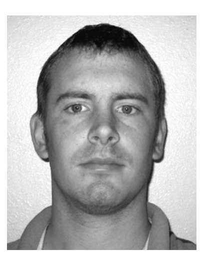

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