An Analytical Approach to Energy-Aware Hybrid Routing for Large Scale Mobile Ad Hoc Networks

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Abstract

We pursue an analytical approach to energy consumption characterization of large scale mobile ad hoc networks. An energy aware hybrid routing strategy is proposed and analyzed. 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 structure of EAGER can be efficiently utilized to reduce routing overhead and overall energy consumption. The cell size and transmission range are optimized analytically. Our analysis shows that EAGER leads to significant performance gains in energy efficiency over pure proactive and reactive strategies.

Index Terms: Ad hoc networks. Routing. Energy efficiency.

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I. 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 [2]–[4] or completely eliminate route discovery, *i.e.,* the message is forwarded directly toward the destination [5]–[8]. 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. Without knowing the location of the destination, the source of a message needs to establish a route to the destination before the message transmission. 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. When a message arrives, it travels through a predetermined route to its destination. 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, assumes no predetermined routes. It finds a route only when a message is to be delivered. Such a strategy 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

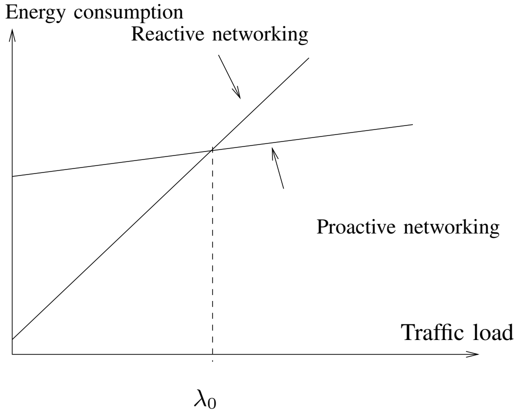

Fig. 1. Energy consumption characteristics: proactive vs. reactive networking.

shown in Fig. 1. For the proactive strategy, energy consumption is dominated by the overhead of link and route updates and the increases of energy consumption with traffic load only comes from the actual delivery of information packets. The reactive strategy, on the other hand, does not incur minimum baseline cost because the overhead associated with route discovery is imposed on a per-message basis. The increase of energy consumption with traffic load, however, is much sharper, and there is a critical traffic load λ_0 above which the proactive strategy is favored. Such characteristics have been demonstrated experimentally [9] and can also be established theoretically under idealized but reasonable network models. See our analysis in Section IV-V.

Energy characteristics shown in Fig. 1 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.

A. Contributions and Limitations

The contribution of this paper is twofold. First, we present an analytical framework to energy consumption of large scale MANET. Using representative proactive and reactive routing protocols, we examine and compare, as a function of node mobility and network traffic load, the energy efficiency of these two routing strategies. The analytical results presented in this paper can be used to obtain the partition of the design space according to energy efficiency for proactive and reactive networking. Such a partition can only be described at the intuitive level previously [10]. We focus on the regime of large scale MANET for which even simulation results are scarce due to the prohibitive simulation time it usually demands.

Second, 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 to ensure the best energy efficiency. Although EAGER utilizes the node position information, it does not require a node to maintain the location or mobility information of any other nodes; it only requires that a node knows its own location. Thus, EAGER belongs to the topology-based approach and differs from the position-based routing protocols. To our best knowledge, EAGER is the first geo-location aided routing protocol that utilizes only the self-location information. It suggests a new approach to utilizing location information in a topology-based routing protocol. Compared to pure proactive and reactive strategies, our analysis shows that EAGER achieves significant performance gain in energy efficiency.

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. As such our analysis of proactive and reactive strategies is intended to capture the essential characteristics of these two routing approaches. It does not, however, include specific improvements such as route caching, local route repair, and probabilistic flooding. Techniques used in our analysis can be adapted to accommodate these specific improvements. Due to space limit, they are not addressed in this paper.

The performance comparison between EAGER and the standard proactive and reactive approaches should be understood in a proper context; they are not compared under identical operating conditions. 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.

B. Related Work and Organization

While analytical results on the energy consumption in large scale MANET is scarce, many energy aware routing protocols have been proposed, see [11]–[17] and references therein. In [16], [18], [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 [10], [20]–[22]. The energy consumption of such protocols, however, is usually not the primary metric for comparison.

EAGER employs the hybrid routing principle, namely locally proactive and globally reactive, which was first proposed by Haas and Pearlman [23], [24] 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.

An analysis on the energy efficiency of proactive and reactive networking strategies can be found in [25]. Different from this paper which focuses on the network layer, [25] extends the concept of proactive and reactive strategies to the physical layer and includes the overhead associated with channel acquisition into the analysis. While [25] considers only the proactive and reactive strategies, the main focus of this paper is to propose a new hybrid routing protocol and demonstrate its potential gain over purely proactive and reactive approaches.

The rest of the paper is organized as follows. In Section II, we present the network and radio models. Basic elements upon which our network-level analysis is built are presented in Section III. In Section IV and V, we analyze, respectively, the energy efficiency of reactive and proactive routing strategies. The hybrid routing protocol EAGER is proposed in Section VI with its performance analyzed in Section VII. Section VIII concludes the paper.

II. THE PROBLEM STATEMENT

A. The Network Model

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[1]. 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

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[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 the knowledge of network topology at each individual node.

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 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.

B. The Radio Model

Nodes, when there is no on-going transmission, 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) [26], [27] 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 study and compare the energy consumption with and without a perfect wake-up scheme. In the calculation of energy efficiency, we ignore the energy consumed in the sleep state and energy consumed by the paging device or energy detector. It is, however, straightforward to incorporate them into the analysis.

When a node is receiving, it consumes E_{rx} Joule/bit; A transmission that covers a neighborhood of radius r consumes $E_{\text{tx}}(r)$ Joule/bit which is given by [28], [29],

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

where α is the path attenuation factor, e_{tx} the energy consumed by the transmitter circuitry, e_{out} the antenna output energy to reach, with an acceptable SNR, the destination unit distance away, and e_{min} the minimum energy radiated regardless of the transmission range. Note that e_{min} imposes a hard limit on the minimum transmission range:

$$r \geq r_0 \stackrel{\Delta}{=} (\frac{e_{\text{min}}}{e_{\text{out}}})^{\frac{1}{\alpha}}. \tag{2}$$

Our goal is to calculate the overall (average) energy $\mathcal{E}$ consumed in one time unit in proactive, reactive, and hybrid networks as a function of the message duty cycle λ_m and network mobility λ_n. We focus on the regime of large scale MANET, *i.e.,* the number N of nodes approaches to infinity by increasing either the node density ρ or the network radius R.

III. ELEMENTS OF ENERGY ANALYSIS

A. The Minimum Transmission Range

In our analysis, the transmission range r is optimized for energy efficiency. We first characterize the interval from which r can assume values.

The first constraint on r is the hardware limit given in (2). The second constraint is network connectivity, *i.e.,* 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 node, we have, from [30],

$$r \geq r_c(N) \overset{N\rightarrow\infty}{\rightarrow} R\sqrt{\frac{\log N}{N}} = \left\{ \begin{array}{ll} \mathcal{O}(\sqrt{\frac{\log N}{N}}) & \rho \uparrow \\ \mathcal{O}(\sqrt{\log N}) & R \uparrow \end{array} \right. . \tag{3}$$

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. Combining (2) and (3), we obtain the minimum transmission range r_{min} for large network as

$$r \geq r_{\text{min}} \overset{\Delta}{=} \max\{r_0, R\sqrt{\frac{\log N}{N}}\}. \tag{4}$$

B. 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 $r \geq r_{\text{min}}$, 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 ρ or R.

While the proof of Proposition 1 is technical (see [25]), 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 to 1. When ρ is fixed and R approaches to infinity, the minimum transmission range r has to increase at the rate of $\sqrt{\log N}$ to ensure network connectivity (see (3)), hence the number of neighbors of each node increases to infinity. Thus, the same conclusion can be reached as in the case of increasing ρ.

With Proposition 1, we can then study the energy consumption in large networks using $\lceil x/r \rceil$ as the number of hops.

C. Point-To-Point Transmission

We now consider the multi-hop communication between a randomly chosen source-destination pair. Consider first the perfect wake-up scheme. In this case, the energy consumed in one hop comes from one transmission and one reception. Let X denote the distance between the source S and the destination D with pdf $p_X(x)$. Let $\mathcal{E}_{\text{S-D}}$ denote the total energy consumed in moving one bit between S and D. From Proposition 1, we have, with probability approaching 1 as $N \to \infty$,

$$\begin{aligned}\mathcal{E}_{\text{S-D}} &= \min_{r \geq r_{\text{min}}} \int_0^{2R} (E_{\text{tx}}(r) + E_{\text{rx}}) h(x,r) p_X(x) \mathrm{d}x \\ &= \min_{r \geq r_{\text{min}}} (E_{\text{tx}}(r) + E_{\text{rx}}) \frac{\mathbb{E}[x]}{r} \\ &= \min_{r \geq r_{\text{min}}} \frac{1}{r} (e_{\text{tx}} + \max\{e_{\text{min}}, e_{\text{out}} r^{\alpha}\} + E_{\text{rx}}) \mathbb{E}[X], \qquad (5)\end{aligned}$$

where for the ease of presentation, we have used x/r instead of $\lceil x/r \rceil$ as the number of hops. Obviously, this approximation does not affect the scaling behavior of the network.

It is easy to show that the transmission range r^* that minimizes (5) is given by

$$r^* = \max\{(\frac{E_{\text{rx}} + e_{\text{tx}}}{e_{\text{out}}(\alpha - 1)})^{\frac{1}{\alpha}}, r_{\text{min}}\}. \qquad (6)$$

We now examine how $\mathcal{E}_{\text{S-D}}$ scales with the network size N. When N is increased by increasing ρ, the minimum transmission range $R\sqrt{\frac{\log N}{N}}$ to ensure network connectivity approaches to 0. We thus have, substituting (6) into (5),

$$\mathcal{E}_{\text{S-D}} \overset{\rho \to \infty}{\longrightarrow} \begin{cases} \alpha e_{\text{out}}^{\frac{1}{\alpha}} \left(\frac{e_{\text{tx}} + E_{\text{rx}}}{\alpha - 1}\right)^{1 - \frac{1}{\alpha}} \mathbb{E}(X) = \mathcal{O}(1) & \text{if } (\frac{E_{\text{rx}} + e_{\text{tx}}}{e_{\text{out}}(\alpha - 1)})^{\frac{1}{\alpha}} > r_0 \\ (\frac{e_{\text{out}}}{e_{\text{min}}})^{\frac{1}{\alpha}} (E_{\text{rx}} + e_{\text{tx}} + e_{\text{min}}) \mathbb{E}(X) = \mathcal{O}(1) & \text{otherwise} \end{cases} \qquad (7)$$

where we have used the fact that $\mathbb{E}[X]$ is a constant independent of the network size N.

When N is increased by increasing R, the optimal transmission range r^* is eventually given by $R\sqrt{\frac{\log N}{N}} = \mathcal{O}(\sqrt{\log N})$. Considering $\mathbb{E}[X] = \mathcal{O}(R) = \mathcal{O}(\sqrt{N})$, we obtain

$$\mathcal{E}_{\text{S-D}} \overset{R \to \infty}{\longrightarrow} e_{\text{out}} (R\sqrt{\frac{\log N}{N}})^{\alpha - 1} \mathbb{E}(X) = \mathcal{O}(\sqrt{N (\log N)^{\alpha - 1}}). \qquad (8)$$

Combining (7,8), we obtain the scaling law for the point-to-point transmission with perfect wake-up scheme as

$$\mathcal{E}_{\text{S-D}} = \begin{cases} \mathcal{O}(1) & \rho \uparrow \\ \mathcal{O}(\sqrt{N (\log N)^{\alpha - 1}}) & R \uparrow \end{cases} \qquad (9)$$

For the case where all neighbors listen to the transmission[2], we have,

$$\begin{aligned}\bar{\mathcal{E}}_{\text{S-D}} &= \min_{r \geq r_{\min}} \int_0^{2R} (E_{\text{tx}}(r) + (\frac{r^2}{R^2}(N-1))E_{\text{rx}}) h(x,r) p_X(x) \mathrm{d}x \\ &= \min_{r \geq r_{\min}} (E_{\text{tx}}(r) + (\frac{r^2}{R^2}(N-1))E_{\text{rx}}) \frac{\mathbb{E}[x]}{r}.\end{aligned}$$

Similar to (9), we obtain the scaling law for the point-to-point transmission without perfect wake-up scheme as

$$\bar{\mathcal{E}}_{\text{S-D}} = \begin{cases} \mathcal{O}(\sqrt{N \log N}) & \rho \uparrow, \ r_0 = 0 \\ \mathcal{O}(N) & \rho \uparrow, \ r_0 > 0 \\ \mathcal{O}(\sqrt{N(\log N)^{\alpha-1}}) & R \uparrow \end{cases} \tag{10}$$

In all cases, the optimal transmission range is given by $r_{\min} \overset{\Delta}{=} \max\{r_0, R\sqrt{\frac{\log N}{N}}\}$. Comparing (9,10) we see that when density ρ increases, the energy consumption without perfect wake-up scheme increases much faster than that with perfect wake-up scheme. The reason for this is that the listening energy dominates when ρ increases. The use of a prefect wake-up scheme thus leads to a different scaling behavior. On the other hand, when the radius R of the network increases, the energy consumed in transmission dominates, resulting in identical scaling behavior of the two cases.

In the following four sections, we analyze the energy consumption of reactive, proactive, and hybrid networking using the basic elements presented above. We focus on the case where perfect wake-up is enabled by the use of paging. We point out that the analysis and the proposed hybrid routing protocol can be extended to incorporate different wake-up schemes.

IV. REACTIVE NETWORKING

In this section, we consider reactive networking. The overall energy consumption comes from route discovery and message transmission. We calculate them separately as follows.

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[2] Energy consumed in overhearing may not be the same as in receiving. For the ease of presentation, we ignore this difference in the analysis. It is however straightforward to incorporate this difference.

A. Route Discovery

For reactive networking, route needs to be established before message transmission. We consider a hop-by-hop routing protocol similar to AODV [31]. As illustrated in Figure 2, when source A has a message for Z, it initiates a route discovery process by broadcasting a request using the network paging sequence to wake up all its neighbors. The request packet contains the source address, the destination address, and a hop count which is zero initially. A neighboring node decodes the request packet, replaces the source address with its own, sets a reverse pointer to the transmitting node, increases the hop count by one, and broadcasts the new request packet. In Figure 2, two different routes from A to Z are illustrated.

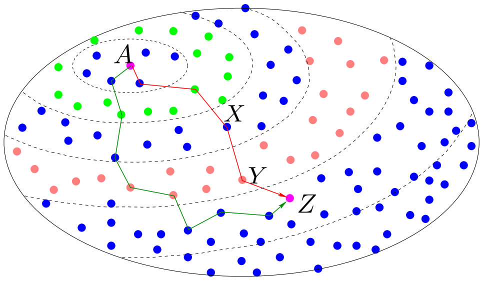

Fig. 2. Transmission of request in reactive networking.

When the request packets reach the destination, Z chooses the node, say Y (see Figure 2), whose request packet has the smallest hop count and transmits a reply packet using the paging sequence of Y so that Y is the only node receiving. Upon receiving the reply, Y sets a pointer to Z and then transmits a reply packet containing the addresses of the destination and its own. This transmission uses the paging sequence of X—the node from which Y receives the request with the smallest hop count. This process continues until a reply reaches the source A. Now a route from A to Z is established.

We now compute the total energy consumed in this route discovery process. Let $B_N = \lceil \log N \rceil$ denote the number of bits for node address and $B_P = \lceil \log(N+1) \rceil$ the number of bits for the N node and one network paging sequences. The total energy consumed in one route discovery process is given by

$$\begin{aligned}\mathcal{E}_{\text{RN,r}}(r) &= (N-1)\{(2B_N + \lceil \log(\frac{2R}{r}) \rceil)(E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) + B_P E_{\text{tx}}(r)\} \\ &\quad + \{2B_N(E_{\text{tx}}(r) + E_{\text{rx}}) + B_P E_{\text{tx}}(r)\}\frac{\mathbb{E}[X]}{r}, \qquad (11)\end{aligned}$$

where $\mathbb{E}[X]$ is the average distance between the source and destination and $\lceil \log(\frac{2R}{r}) \rceil$ the number of bits for the hop count. The first term in (11) is the energy consumed in the transmission of requests: every node transmits once consuming $E_{\text{tx}}(r)$; for each transmission, all neighboring nodes decode, consuming $\frac{r^2}{R^2}(N-1)E_{\text{rx}}$. The second term is the energy consumed in the transmission of replies: every reply packet contains $2B_N$ bits for the addresses of the destination and the relaying node, $E_{\text{tx}}(r) + E_{\text{rx}}$ is the transmitting and listening energy in one hop, and $\frac{\mathbb{E}[X]}{r}$ the asymptotic average number of hops from the source to the destination. Note that we ignore the low energy cost in the detection of paging sequences. Thus, the transmission of a paging sequence only costs energy at the transmitter.

B. Message Transmission

Energy consumption in message transmission with a perfect wake-up scheme has the same expression as in the point-to-point traffic analysis given in (5). The only difference is that the optimization over the transmission range r should be carried out on the total energy consumption including the overhead associated with route discovery. Since the information on the relaying node is provided by the perfect wake-up scheme (the node that is woken up is the relaying node), only the addresses of the source and the destination need to be embedded in the message. We thus have, for the transmission of one message,

$$\mathcal{E}_{\text{RN,m}}(r) = \{(2B_N + B_M)(E_{\text{tx}}(r) + E_{\text{rx}}) + B_P E_{\text{tx}}(r)\}\frac{\mathbb{E}[X]}{r}, \qquad (12)$$

where $2B_N$ is the number of bits for the addresses of the source and the destination, B_M is the message length.

We now compute the total energy consumption $\mathcal{E}_{\text{RN}}$ for reactive networking in one unit time within which total $\lambda_m N$ (on the average) messages are generated. For large networks with uniform traffic and fixed message arrival rate λ_m, the probability that a route established for one message can be used for another message approaches 0 as N goes to infinity[3]. Thus, on the average, $\lambda_m N$ route discovery processes are initiated within one unit time. We have

$$\mathcal{E}_{\text{RN}} = \min_{r \geq r_{\text{min}}} \lambda_m N \left(\mathcal{E}_{\text{RN,r}}(r) + \mathcal{E}_{\text{RN,m}}(r)\right). \tag{13}$$

The above optimization can be done numerically. Similar to (9), the scaling behavior of the reactive routing strategy when either ρ or R increases can be obtained.

V. PROACTIVE NETWORKING

A. Route Maintenance

With proactive networking, network topology and route information are maintained regardless of the message arrivals. We consider here the standard link state routing strategy. 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 the network. Assume that the ”hello” message is transmitted at the rate (λ_n) of the topology change. The energy consumed in

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[3] We do not consider cache and local route repair. The probability that a route established for one message can be used for another is thus the probability that two messages are generated for the same source-destination pair before the route becomes invalid due to topology change. It is easy to show that the probability that two messages are generated for the same source-destination pair within a time period of T is $N \begin{pmatrix} \lambda_m T \\ 2 \end{pmatrix} (\frac{N-1}{N})^{\lambda_m T-2}(\frac{1}{N})^2$ which approaches 0 as $N \to \infty$ for any $T > 0$. Thus, for a mobile network with zero probability of being stationary, the probability that a route established for one message can be used for another approaches 0 as $N \to \infty$.

proactive route maintenance in one unit time is given by

$$\begin{aligned}\mathcal{E}_{\text{PN,r}}(r) &= N\lambda_n\{B_N(E_{\text{tx}}(r)+\frac{r^2}{R^2}(N-1)E_{\text{rx}})+B_PE_{\text{tx}}(r)\}\\ &\quad +N^2\lambda_n\{B_N\frac{r^2}{R^2}(N-1)(E_{\text{tx}}(r)+\frac{r^2}{R^2}(N-1)E_{\text{rx}})+B_PE_{\text{tx}}(r)\}, \qquad (14)\end{aligned}$$

where the first term is the energy consumed in the transmission of "hello" messages: $B_N = \lceil \log N \rceil$ 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.

B. Message Transmission

The analysis here is the same as in reactive networking. From (12) we obtain

$$\mathcal{E}_{\text{PN,m}}(r) = \{(2B_N+B_M)(E_{\text{tx}}(r)+E_{\text{rx}})+B_PE_{\text{tx}}(r)\}\frac{\mathbb{E}[X]}{r}. \qquad (15)$$

The total energy consumption in one unit time is then given by

$$\mathcal{E}_{\text{PN}} = \min_{r\geq r_{\text{min}}}\left(\mathcal{E}_{\text{PN,r}}(r)+\lambda_m N\mathcal{E}_{\text{PN,m}}(r)\right). \qquad (16)$$

C. Proactive vs. Reactive Strategies

We now compare energy consumption characteristics of proactive and reactive strategies. We consider a large network with 30k nodes randomly distributed on a disk with radius $R = 1000$ meters. Shown in Figure 3 is the total energy consumed in one unit time as a function of the message duty cycle λ_m. We observe that significant improvement in energy efficiency can be achieved by reactive networking when the message duty cycle is low. When the message duty cycle is high, however, proactive networking is more efficient.

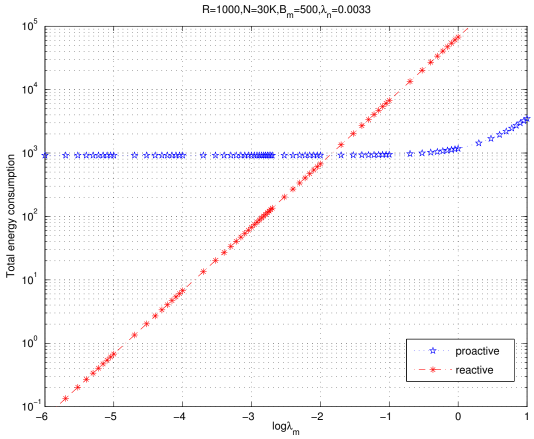

Fig. 3. Energy consumption of proactive and reactive networking.

From (16,13) we can solve for the cross-over point λ_0 below which the reactive approach is desired over the proactive approach.

$$\lambda_0 = \frac{\mathcal{E}_{\text{PN,r}}(r^*)}{N\mathcal{E}_{\text{RN,r}}(r^*)}, \tag{17}$$

where r^* is the optimal transmission range. It can be shown that $r^* = r_{\text{min}}$ for both proactive and reactive strategies when the network size N is large.

VI. HYBRID NETWORKING: THE PROTOCOL

In this section, we present the Energy Aware GEo-location aided Routing (EAGER) protocol as an example of hybrid networking. Its energy efficiency is analyzed and compared with that of proactive and reactive networking in Section VII.

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.

A. Network Partition

As shown in Figure 4, the network is partitioned into cells; 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 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 3 paging sequences to ensure that any two adjacent cells do not share the same paging sequence.

B. Route Discovery

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 VI-C). 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 as analyzed in Section V although other proactive routing protocols may be used.

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

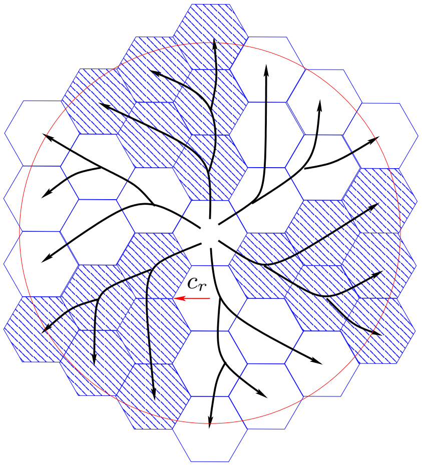

Fig. 4. Traffic flow of a route discovery request (assuming the source is located in the center cell).

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 Figure 4 where, without loss of generality, we assume the source is located in the center cell of the network. As seen from Figure 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, the 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 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.

Definition Let α be the cell of the source. The network is partitioned into rings of cells around α. (See Fig. 5-Left). The level of a cell with respect to α is the level of the ring to

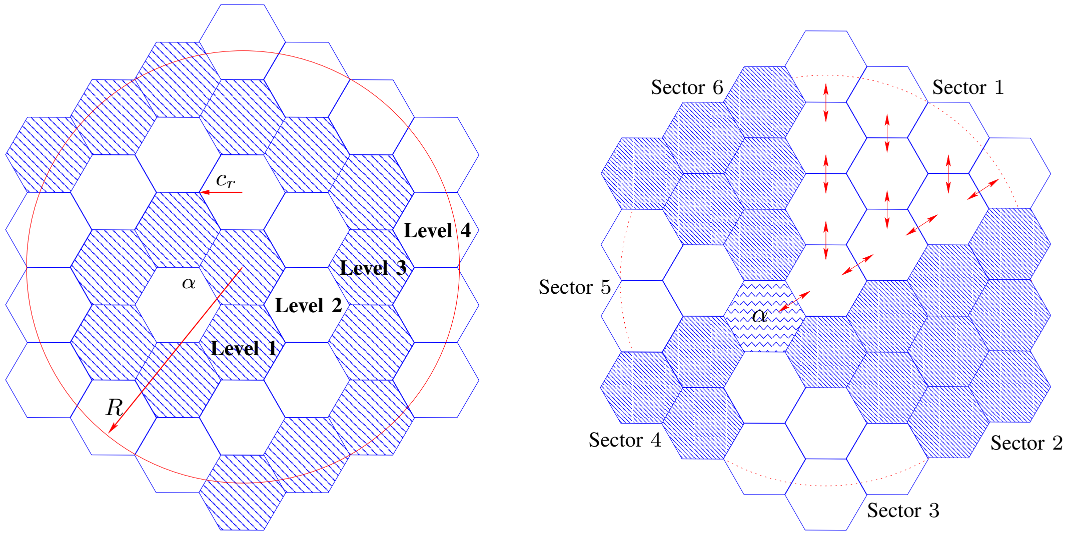

Fig. 5. Cell structure of EAGER: level (left) and adjacent cells (right) (R: network radius; c_r: cell size; α: source cell).

which the cell belongs.

Level is a measure of the distance between two cells. As shown in Figure 5-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 5-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 5-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 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 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 6-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 6-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.

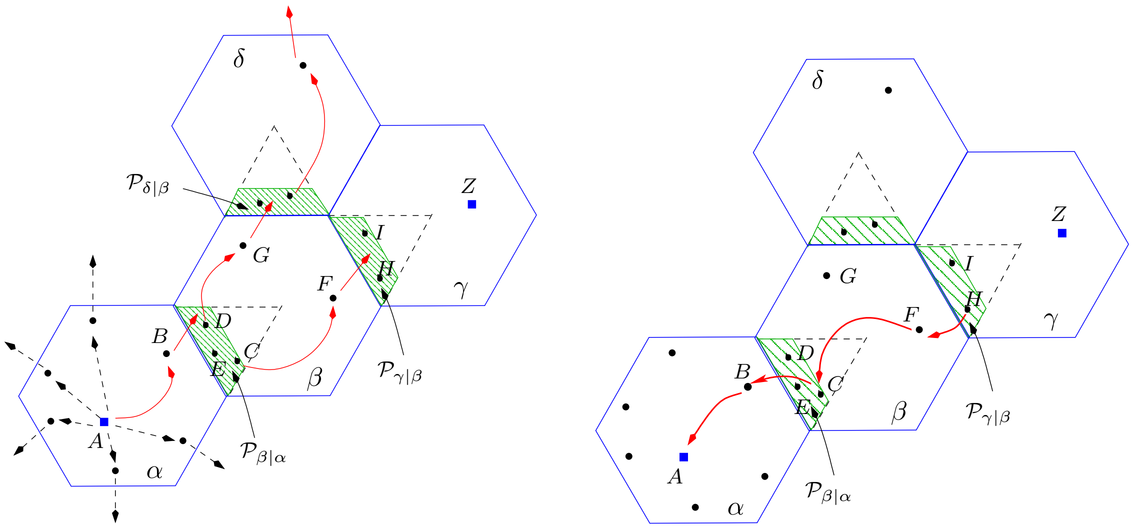

Fig. 6. Inter-cell route discovery: transmission of request (left) and reply (right).

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 6-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 5-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[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 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

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

In our example, assume $d_{\text{min}}(\mathcal{P}_{\beta|\alpha}, \mathcal{P}_{\beta|\gamma})$ is given by the distance between C and F[5]. 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.

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

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

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 6-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.

We make the following remarks on the inter-cell 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 $i+1$ only has one adjacent cell on level i by the definition of "adjacency". This ensures that each cell is visited at most once during the search of the destination. The structure of the periphery area can free a large percentage of nodes from the 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 to which cell to propagate the request. Similarly, a node can determine whether it is in the periphery thus possibly responsible for relaying after receiving a request from a node outside its cell.

- Level, adjacent cells, and periphery are all defined w.r.t. the cell of the source. Thus, the cell ID of the source needs to be embedded in all request and reply packets.

C. *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 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

$$\{c_r^*, A_p^*, r_I^*\} = \arg\min \lim_{t\to\infty} \frac{\mathcal{E}_t(c_r, A_p, r_I)}{t}, \quad s.t.\ P_o(c_r, A_p) \leq p_o,\ r_I \geq r_{\text{min}}. \tag{18}$$

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 is presented in Section VII.

VII. HYBRID NETWORKING: THE ANALYSIS

In this section, we analyze the energy efficiency of EAGER. As in proactive and reactive networking, energy consumption comes from route discovery and message transmission. In EAGER, route discovery consists of two elements: the in-cell proactive routing and the cross-cell reactive routing. Before calculating the energy consumption associated with each components, 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 w.r.t. 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

$$B_N = \lceil \log N \rceil, \; B_C = \lceil \log M \rceil, \; B_P = \lceil \log(N+3) \rceil. \tag{19}$$

A. In-Cell Proactive Routing

Similar to the analysis of proactive strategy given in Section V, we consider the standard link state routing scheme. The only difference here is that the nodes located in a periphery area need to flood the ID of the cell to which they are adjacent. Similar to (14), we obtain the total energy consumed in in-cell proactive routing in one unit time as

$$\begin{aligned} \mathcal{E}_{\text{HN,I}}(r_I) &= N\lambda_n\{B_N(E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) + B_P E_{\text{tx}}(r)\} \\ &+ \frac{N^2}{M}\lambda_n\{(B_N + B_C)\frac{r^2}{R^2}(N-1)(E_{\text{tx}}(r) + \frac{r^2}{R^2}(N-1)E_{\text{rx}}) + B_P E_{\text{tx}}(r)\}. \end{aligned} \tag{20}$$

B. Cross-Cell Reactive Routing

When node A in cell α has a message for Z, with probability[6] $1 - 1/M$, Z is in a different cell. A route has to be established before the message transmission. We divide energy consumption of this 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 Figure 6-left). These

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[6] We consider here the uniform traffic where a packet generated by a node is equally likely to be intended for any other node in the network. The analysis, however, can be easily extended to different traffic patterns as considered in Section VII-D.

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

$$\mathcal{E}_{\text{HN,C1}} = 6\{2B_N(E_{\text{tx}}(r_I) + E_{\text{rx}}) + B_P E_{\text{tx}}(r_I)\}\bar{h}_I, \tag{21}$$

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.

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 Figure 6-left. 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 transmission energy parameterized by r_C. Below we calculate the minimum value of A_p.

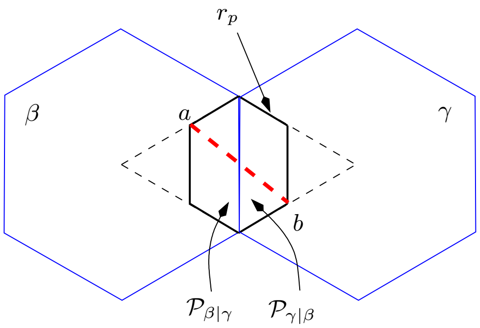

Fig. 7. The size of periphery.

Consider the propagation of request from cell β to γ as shown in Figure 7. One route discovery involves total $2(M-1)$ periphery areas, half of which contains nodes for receiving the request from a lower level, 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 [32], the topological difference between a network with N uniformly distributed nodes and a two-dimensional Poisson distributed network with the same density ρ is negligible when N is large. We thus have

$$(1-e^{-A_p\rho})^{2(M-1)} \geq 1-p_o, \quad \textit{i.e.,} \quad A_p \geq \underline{A_p} \triangleq -\frac{1}{\rho}\log(1-(1-p_o)^{\frac{1}{2(M-1)}}). \tag{22}$$

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 equal to the distance between a and b in Figure 7. We thus have

$$r_C = \sqrt{c_r^2 - 2c_r r_p + 4r_p^2}, \quad \text{with } r_p = c_r - \sqrt{c_r^2 - \frac{4\sqrt{3}}{3}\underline{A_p}}, \tag{23}$$

where r_p is the minimum length of the sides of the periphery (see Figure 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

$$\bar{A}_p = \begin{cases} c_r r_c + \frac{\sqrt{3}}{3}r_c^2 & \text{if } r_c \leq \frac{\sqrt{3}}{2}c_r \\ A_c(c_r) - (2\sqrt{3}c_r^2 - 3r_c c_r + \frac{\sqrt{3}}{3}r_c^2) & \text{otherwise} \end{cases}, \tag{24}$$

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

$$\mathcal{E}_{\text{HN,C2}} = (M-1)\{(2B_N + B_C)(E_{\text{tx}}(r_C) + \bar{A}_p\rho E_{\text{rx}}) + B_P E_{\text{tx}}(r_C)\}, \tag{25}$$

where $M-1$ is the maximum number of cross-cell transmissions during the propagation of the request packets in one route discovery, $2B_N + B_C$ 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 $\bar{A}_p\rho$.

The reason that the minimum value of A_p can be obtained by considering the outage probability of a single route discovery lies in the particular shape of the periphery. When multiple nodes initiate route discovery simultaneously, a cell may have several adjacent cells defined w.r.t. different source cells, resulting in several periphery areas. The particular definition of periphery ensures that the periphery areas of a cell do not overlap. Thus, the number of nodes contained in one periphery is independent of those of other periphery areas for Poisson field. This enables us to obtain the minimum value of A_p by considering a single route discovery.

We point out that it is possible the minimum value of A_p given in (22) 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 $r_C = 2\sqrt{3}c_r$, *i.e.,* the transmission of a node randomly located in a cell can be heard by all nodes in the adjacent cell. In this case, the minimum number of required cell paging sequences can be larger than 3 in this case.

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 Figure 6-left. 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 (21), we have

$$\mathcal{E}_{\text{HN,C3}} = (M - 1 - 6L)\bar{h}_I\{(2B_N + B_C)(E_{\text{tx}}(r_I) + E_{\text{rx}}) + B_P E_{\text{tx}}(r_I)\}, \tag{26}$$

where $\bar{h}_I = \lceil \frac{2c_r}{r_I} \rceil$, as defined earlier, 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 occur during this process depends on the level of the destination w.r.t. the source cell α. We obtain an upper bound on the average level of the destination cell by assuming that α is the geographic center of the network and there are total $2L$ levels. The number of cells in this case is $M' = 1 + 6L(2L + 1)$. Since the probability that the destination cell is on level i is $6i/(M' - 1)$, we obtain an upper bound on the average level l_D of the destination cell as

$$\mathbb{E}[l_D] \leq \bar{l}_D \stackrel{\Delta}{=} \sum_{i=1}^{2L} i \frac{6i}{M' - 1} = \frac{4L + 1}{3}. \tag{27}$$

Recall $\bar{h}_I$ is an upper bound on the number of hops for in-cell transmission. We obtain the total energy consumed in the transmissions of reply as

$$\begin{aligned}\mathcal{E}_{\text{HN,C4}} &= \{(2B_N + B_C)(E_{\text{tx}}(r_I) + E_{\text{rx}}) + B_P E_{\text{tx}}(r_I)\}\bar{h}_I \bar{l}_D \\ &\quad +\{(2B_N + B_C)(E_{\text{tx}}(r_C) + E_{\text{rx}}) + B_P E_{\text{tx}}(r_C)\}\bar{l}_D, \qquad (28)\end{aligned}$$

where the first term is the energy consumption for in-cell transmission with range r_I and the second term the energy consumption for cross-cell transmission with range r_C.

From (21,25,26,28) we obtain the total energy $\mathcal{E}_{\text{HN,C}}(r_I, A_p)$ consumed in one cross-cell route discovery as

$$\mathcal{E}_{\text{HN,C}} = (1 - \frac{1}{M})(\mathcal{E}_{\text{HN,C1}} + \mathcal{E}_{\text{HN,C2}} + \mathcal{E}_{\text{HN,C3}} + \mathcal{E}_{\text{HN,C4}}), \qquad (29)$$

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

C. 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 the paging sequences activating nodes on the route, and B_M the message length. Similar to the analysis of the energy consumption in the transmissions of route reply (see (28)), we obtain an upper bound on the energy consumed in the transmission of one message

$$\begin{aligned}\mathcal{E}_{\text{HN,M}} &= \{(2B_N + B_M)(E_{\text{tx}}(r_I) + E_{\text{rx}}) + B_P E_{\text{tx}}(r_I)\}\bar{h}_I \bar{l}_D \\ &\quad +\{(2B_N + B_M)(E_{\text{tx}}(r_C) + E_{\text{rx}}) + B_P E_{\text{tx}}(r_C)\}\bar{l}_D. \qquad (30)\end{aligned}$$

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

$$\mathcal{E}_{\text{HN}} = \min_{c_r, A_p, r_I} (\mathcal{E}_{\text{HN,I}} + \lambda_m N \mathcal{E}_{\text{HN,C}} + \lambda_m N \mathcal{E}_{\text{HN,M}}), \qquad (31)$$

where $\mathcal{E}_{\text{HN,I}}$, $\mathcal{E}_{\text{HN,C}}$, and $\mathcal{E}_{\text{HN,M}}$ are given by (20),(29), and (30), respectively. The above optimization can be done numerically.

D. Comparison of Energy Efficiency

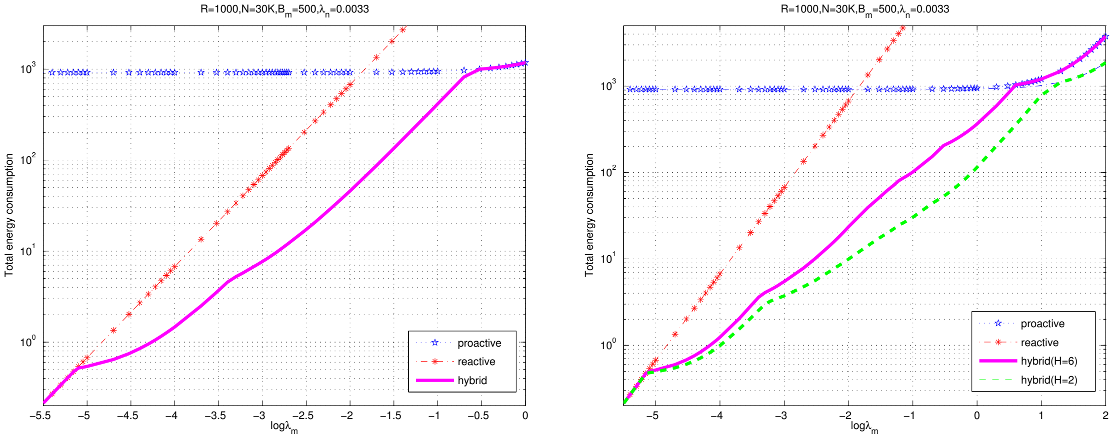

Fig. 8. Energy consumption of proactive, reactive, and hybrid networking: uniform traffic (left) and localized traffic (right).

We now compare the energy efficiency of the hybrid networking with that of the proactive and reactive networking. We consider the same network setup used to obtain results in Figure 3. The outage probability p_o is set to 0.01. Shown in Figure 8 is the numerical results on the total energy consumption as a function of the message duty cycle λ_m. In Figure 8-left, we consider uniform traffic pattern, *i.e.,* a message generated by a node is equally likely to be intended for any other node in the network. We observe that at low message duty cycle, the hybrid routing protocol EAGER converges to a pure reactive scheme, *i.e.,* the cell radius c_r goes to 0. When the message duty cycle is high, EAGER converges to a pure proactive scheme; the cell radius approaches to R. When the message duty cycle is in the range of $[10^{-5}, 10^{-0.5}]$, hybrid networking can provide up to nearly 2 orders of magnitude of reduction in total energy consumption over the minimum offered by the proactive and reactive networking. We point out that the performance analysis of EAGER provides an upper bound on energy consumption. The potential gain may be more significant.

Shown in Figure 8-right is the comparison of energy consumption under a localized traffic pattern. In this case, the source-destination distance is exponentially distributed with a mean of H hops. 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 patter, however, EAGER achieves better energy efficiency when the traffic becomes more localized.

VIII. CONCLUSION

We present in this paper an analytical approach to energy consumption of large scale MANET. Our goal is to investigate interdependencies of network parameters and operation regions where reactive networking is more energy efficient than proactive networking. The analysis presented in this paper allows the examination of different design scenarios by setting specific network parameters: the network mobility and the message arrival rate.

A hybrid protocol that optimally combines the proactive and reactive designs are proposed. Our analysis shows that by designing a more sophisticated hybrid protocol, significant improvement in energy efficiency can be achieved over a simple switch between the proactive and the reactive strategies.

One should keep in mind that our analysis is not intended to match a certain network implementation. Simplifying assumptions are made for they are necessary to make analysis tractable. The analysis presented here should be viewed as a baseline benchmark with which simulation based approach can be cross-checked.

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