Hybrid Cellular-MANETs: An Energy-Aware Routing Design

Chenyu Zheng Lijun Chen Douglas Sicker
University of Colorado at Boulder, USA
Emails: {chenyu.zheng, lijun.chen, douglas.sicker}@colorado.edu

***Abstract*—It is well-recognized that our dependence on mobile communications grows; however, users of wireless devices may encounter inadequate coverage due to a variety of shortage and outage circumstances. This is an especially urgent issue in disaster areas where the access to outside world is critical for rescue operations. In this paper, we present a self-organizing communication framework for extending wireless coverage for mobile devices, without requiring modifications of existing wireless infrastructures. Participating devices form a hybrid cellular – mobile ad hoc network, relaying data off net through the nodes that have cellular connections. We design a low-complexity, energy-aware, multi-path data routing mechanism for this framework. The proposed routing includes two major components: a baseline routing that includes a locally reactive and hence low-complexity routing sub-component to handle mobility; and an energy-aware multi-path routing that is motivated by an energy optimization problem and uses only local information. Packet-level simulations show that the proposed routing scheme achieves good performance in delay, packet delivery, and energy consumption. In addition, we implement this framework on Android devices and conduct phone-in-the-loop emulations. The results from the emulation show that the proposed routing scheme can achieve more efficient energy utilization.**

I. Introduction

The dependence on mobile communications in our society is growing. However, the coverage to mobile devices can be inadequate due to various infrastructure and outage circumstances. The sporadic loss of telecommunication service and the shortage of open WiFi access points may cause coverage problems in rural settings. In disaster areas, the damage to local wireless infrastructures, such as failed base stations, antennas, cables, and power and cooling system, may limit critical network access [1], [2], [3], [4]. In this paper, we present a self-organizing communication framework for mobile devices in disaster areas to extend wireless coverage.

This framework allows the participating devices to form a hybrid cellular – mobile ad hoc network (MANET) [5], by connecting to each other through their WiFi interfaces without dependence on the wireless infrastructure. A portion of the devices or members called *gateway nodes* have cellular access capable of relaying packets to destinations off the MANET. By employing the devices that have sufficient battery life and wireless link capacity to relay data, the hybrid cellular-MANET is able to extend wireless coverage.

The challenges of this framework are as follows:

- *Responsiveness* – The mobility of the users/devices cause continuous topology changes in the hybrid cellular-MANET. The data routing mechanism of the framework must be able to quickly adapt to the changing topology.
- *Energy Efficiency* – Battery energy is a critical resource that should be used efficiently for the whole network. The framework must incorporate energy efficiency, in particular in its routing design.
- *Easy Deployment* – In a disaster area, it is difficult to deploy wireless infrastructure in a timely manner. The framework must be able to extend wireless coverage for mobile devices in the area without modifications of the existing wireless infrastructure.

Previous work in hybrid MANET routing, see, e.g., [6], [7], [8], [9], [10], have various limitations such as low scalability and inefficient resource utilization, and cannot effectively address the above challenges. In this paper, we design a low complexity, energy-aware, multi-path data routing mechanism, using self-organization (SO) as the control mechanism. SO allows distributed participants to collaboratively achieve global goals based on pure local information and interactions [11], [12], possesses the desired properties such as high scalability, low overhead, and robustness, and can effectively address the above challenges.

Specifically, our routing scheme includes two components: a baseline routing that generates an effective connectivity graph; and an energy-aware multi-path routing on the effective connectivity graph. The baseline routing uses the expected transmission number as the link metric, and includes a locally reactive and hence low-complexity routing sub-component to handle mobility. The energy-aware routing is based on distributed decomposition of an energy optimization problem and uses only local information. Packet-level simulations show that the proposed routing scheme achieves good performance in delay, packet delivery, and energy consumption. In addition, we implement the self-organizing communication framework in the form of an Android service. Mobile devices that run on Android 4.0 (and above) operating systems can install it without root privilege and use it to form a hybrid cellular-MANET to extend wireless coverage. We leverage this implementation in the phone-in-the-loop emulation to evaluate the energy efficiency of our design. The results from the emulation show that the proposed routing can achieve more efficient energy utilization.

The rest of the paper is organized as follows. Section II briefly reviews the related work. Section III describes the system design of the self-organizing communication framework.

Section IV presents the implementation and performance evaluation of the proposed energy-aware multi-path routing protocol, and Section V concludes the paper.

II. Related Work

A. Mobile Communication in Disaster Areas

Manoj et al. [13] summarized communication challenges in disaster areas, showing that people in a disaster zone need to provide continual information updates, such as their position, physical and mental status, and surrounding environment, for both rescue-assisting and social-comforting purposes. They also desire periodic information updates on general damage status, situation of their families and friends, and the progress of the relief process. This information is not only useful for self-rescue, but also helpful for easing the emotional volatility aggravated by isolation. As a result, we focus on extending wireless coverage to provide text messaging, social networking, and voice services among mobile devices in the disaster area and hosts in the Internet.

B. Hybrid MANETs Control

State-of-the-art hybrid MANET control can be applied to the data forwarding for extending wireless coverage; however, there is room for improving each of the following mechanisms.

The flat multicast hybrid communication design [6], [7] relies on MANET routing mechanisms to discover paths between the nodes that are outside the coverage of cellular base stations and gateway nodes. Different MANET data forwarding schemes, including both the classic approaches and self-organizing approaches, can be selected based on the application scenarios of the hybrid structure. However, this type of design does not provide a gateway selection mechanism for the out-of-coverage nodes. These nodes normally will select the gateway nodes that are near them, which causes congestion in the network and unbalanced battery consumption for gateway nodes.

The tree-based multicast hybrid communication design [8] employs wireless mesh routing mechanisms to build a tree-based structure from the nodes that are outside the coverage of cellular base stations toward the gateway nodes. This type of design requires gateway nodes to periodically flood control messages to the network, which can cause considerable communication overhead.

The unicast hybrid communication design [10] requires the out-of-coverage nodes sniff neighboring nodes' data transmission in order to build two-way paths between the nodes that are outside of the coverage of cellular base stations and the gateway nodes. This type of design does not rely on the multicast action, which saves both the bandwidth and battery life for nodes. However, the route discovery procedure requires that all the intermediate nodes between the source nodes and the base station have recent upstream data transmission, which results in high latency.

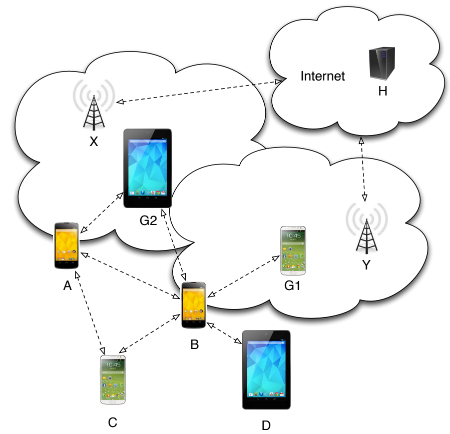

Fig. 1: System architecture of the hybrid cellular-MANET

III. System Design

A. System Architecture

As shown in Figure 1, existing cellular base stations, such as X and Y, provide infrastructure coverage. Participating devices are connected with each other through their 802.11 interfaces. Devices with sufficient battery charge level and cellular link capacity, such as $G1$ and $G2$, act as *gateway nodes* relaying packets from other peers to hosts in the Internet, such as H, using their cellular interfaces. Devices that have limited cellular access, i.e., *terminal nodes*, such as C and D, will forward their Internet packets to appropriate gateway nodes through 802.11 P2P of a number of *relay nodes*, such as A and B, which have adequate battery charge level.

1) Role Determination: Mobile devices in the hybrid MANET would individually determine their role, i.e., gateway nodes, relay nodes, or terminal nodes, based on their current cellular bandwidth and battery charge level:

- When a node does not have enough cellular bandwidth to communicate with hosts in the Internet directly, it acts as a terminal node.
- When a node has sufficient battery charge level for 802.11 P2P relay, it acts as an intermediate relay node to help forward data packets.
- When a node has extra cellular bandwidth and adequate battery charge level, it acts as a gateway node to help offload Internet traffic of terminal nodes.

Both cellular bandwidth and battery charge level can be observed locally from callback functions of the mobile operating system. Based on the above criteria, a node can assume several roles at the same time. For example, a gateway node serves as a relay for other nodes; and a terminal node may be a relay for another node.

We use two thresholds on the battery charge level instead of a static threshold for the role determination of gateway and relay nodes. The high threshold is used for a node to decide if it wants to take the responsibility of serving as a gateway (or relay) node. The low threshold is used for a node to decide if it should be released from its duty. This can improve the utilization of qualified mobile devices. In our experiments in Section IV, 50% and 30% of battery charge levels are used for relay thresholds, and 70% and 50% battery charge levels are used for gateway thresholds, but other threshold values can be chosen as well.

B. Routing

We consider application scenarios of the hybrid cellular-MANET where the disaster information at different nodes needs to be reported and sent to, e.g., a command center (that is connected to the Internet) for, for example, disaster evaluation. We now develop an energy-aware routing scheme for such applications.

1) Network Model: Consider a hybrid cellular-MANET with a set M of nodes, of which a subset W are gateway nodes. The gateway nodes will connect to a set B of base stations that are connected to the Internet and thus the command center, denoted by a virtual node d. Node d is thus the destination of all communications for the applications we consider. We assume that each gateway node is served by only one base station, and denote the connection of a base station to d by a virtual link with weight 0 (independent of the link metric used), as we focus on the routing within the hybrid cellular-MANET, i.e., how to transfer data from the mobile nodes to the base stations.

Let $N = M \cup B \cup d$. The connectivity of the network is denoted by a set $\hat{L}$ of directed links, where $(i, j) \in \hat{L}$ if node $i \in N$ can transmit directly to node $j \in N$. Each link (i, j) achieves an average data rate c_{ij}. The data rates c_{ij} depend on the specific medium access control (MAC) protocol used. However, in this paper we do not consider the MAC design, and thus c_{ij} is assumed to be given. We will see later that, even though the average data rates c_{ij} are assumed to be given, we do not need to know their values. Let $\hat{C} = \{c_{ij}\}_{(i,j)\in\hat{L}}$. $\hat{G} = (N, \hat{L}, \hat{C})$ is thus the connectivity graph of the hybrid cellular-MANET.

We assume that the network is relatively static, with infrequent mobility. Our routing scheme includes two components: a baseline routing that generates an effective connectivity graph; and an energy-aware multi-path routing on the effective connectivity graph.

2) Baseline Routing: The goal of the baseline routing is to construct an effective connectivity graph for data transfer, so as to improve the communication performance in terms of delay and reliability, etc. We will use expected transmission number (ETN) as the link metric, which can be estimated by probing at network layer or using information from the MAC layer. As the network is relatively static with infrequent mobility, the baseline routing scheme is mainly proactive, but supplemented by a locally reactive scheme based on the mobility of the node.

a) Proactive baseline routing: Each gateway node $w \in W$ will announce its existence and start the routing process. We use distance-vector routing algorithm to find out the shortest paths to d. However, we allow multi-path routing, where each node can send to any neighbors who have a closer shortest path to d. This defines an effective connectivity graph $G = (N, L, C)$ for the network, with $L \subset \hat{L}$ and $C = \{c_{ij}\}_{(i,j)\in L}$. There are two reasons for doing this: to improve delay and reliability performance and to reduce complexity in the energy-aware routing component.

Each node in the network maintains a path ETN value, i.e., the weight of the currently-known shortest path to the virtual node d, and will announce its current path ETN value to the neighboring nodes on the connectivity graph $\hat{G}$. Each node will update its shortest path to d and the corresponding ETN value, based on the path ETN values of the neighboring nodes.

Each node i also maintains a set $\mathcal{N}_i$ of neighboring nodes who have a closer shortest path to d. The set $\mathcal{N}_i$ will be updated, when node i receives the update on its neighbors' current ETN values and updates its own ETN value.

When the distance-vector routing algorithm converges, each node will know the path ETN value of its shortest path to the virtual node d, as well as the set $\mathcal{N}_i$ of neighboring nodes who have a closer shortest path to d. As opposed to the single-path shortest path routing, here we consider multi-path routing where each node will forward the data to all its neighbors in $\mathcal{N}_i$. The routing then reduces to the problem of deciding how much data should be forwarded to each node in $\mathcal{N}_i$, which we will address in Section III-B3.

b) Locally reactive baseline routing: As wireless devices move, the existing paths may have worse performance in delay and reliability, or even become broken. Therefore, routing needs to react and adapt to node mobility. However, reactive routing that (re-)calculates a new end-to-end path may incur high cost in communication/signaling overhead. Therefore, we consider a locally reactive routing scheme, where a moving node and its neighbors locally modify the path that is obtained from the above proactive routing. This will on one hand improve the path quality and on the other hand reduce the routing complexity greatly, as explained below.

To understand the basic idea behind the locally reactive routing, consider a segment from node i to node j and then to node k of a path P. When node j is moving, depending on how far it moves away from nodes i and k, the path segment $i \to j \to k$ may have larger ETN than a "direct" path segment $i \to j$ or a path segment $i \to h \to k$ through another neighboring node h does. Under this situation, the reactive routing will modify the path P locally to use $i \to j$ or $i \to h \to k$. Also, if node j moves "into" a segment $\hat{i} \to \hat{k}$ of an other path $\hat{P}$, the ETN of $\hat{i} \to \hat{k}$ may become larger than that of $\hat{i} \to j \to \hat{k}$. Under this situation, the reactive routing will modify the path $\hat{P}$ locally to use $\hat{i} \to j \to \hat{k}$. A similar situation is that, when node j moves near a segment $\hat{i} \to \hat{j} \to \hat{k}$ of an other path $\hat{P}$, the ETN of $\hat{i} \to \hat{j} \to \hat{k}$ may be larger than that of $\hat{i} \to j \to \hat{k}$ and the reactive routing will modify the path $\hat{P}$ locally to use $\hat{i} \to j \to \hat{k}$.

To deal with the above situations, we design a local routing scheme initiated by the moving node to update ETN values in the group that consists of the moving node itself and its old/new neighbors. The moving node first asks all of its neighbors to announce their current path ETN values to other nodes in the group. Each node then updates its shortest path to d with a new ETN value, based on the path ETN values of neighboring nodes in the group. The corresponding ETN values in the set $\mathcal{N}_i$ of neighboring nodes who have a closer shortest path to d in each node is updated as well.

A key issue that remains to be addressed is when or how often the locally reactive routing should be employed: we do not want to initiate it too often, since this would incur high overhead; we do not want to initiate it too seldom, since this would miss opportunities to improve the path quality. Basically, we only initiate the local routing procedure when a node moves by a large enough distance. To achieve this, we need to obtain the motion and location information of wireless devices.

Movement of a device is detected using the built-in acceleration sensor, based on the movement hint extraction procedure proposed by Ravindranath et al. [14]. The accelerometer of most smart devices usually stays on in order to perform functions such as detecting rotation of the screen. In addition, it consumes much less battery energy than GPS does. As a result, we use it to continuously sample the magnitude of the acceleration of participating devices. Each time the standard deviation of the acceleration of a device over a sliding window of samples exceeds the predefined threshold, we will report that this node is moving, and initialize the locally reactive routing. When the standard deviation is within this threshold for a number of consecutive sliding windows, we report that this node becomes stationary, and the locally reactive routing will be stopped. The proposed locally reactive routing trades off optimality for low complexity. It gives a better path than the original one, which may not be the best "reactive" path. But it incurs low complexity, as it reacts to mobility locally and modify the existing path locally.

3) Energy-Aware Multi-Path Routing: The baseline routing generates an effective connectivity graph for data transfer on the hybrid cellular-MANET. We now consider energy efficiency in routing decisions on the distributively generated effective connectivity graph.

Associated with each node $i \in M$ is an average data rate r_i for the data with source at i and an initial battery level B_i. Suppose the flow rate at link (i, j) is f_{ij}. Then, we have the following flow conservation constraint:

$$\sum_{j:(j,i)\in L} f_{ji} + r_i = \sum_{j:(i,j)\in L} f_{ij}, \quad i \in M. \tag{1}$$

Note that here we consider the balance of the aggregate flow but not the balance of each commodity flow at each node, since all the flows have the same destination d. The aggregate flow balance (1) also leads to decreased algorithm and implementation complexity.

We may have to add an additional constraint on the schedulability, depending on how we handle medium access control (MAC). However, as mentioned before, in this paper we do not consider MAC, but instead we assume that each link $(i, j) \in L$ achieves an average data rate c_{ij}. We thus have the following link rate constraint:

$$f_{ij} \leq c_{ij}. \tag{2}$$

Assume that for each node $i \in M$, it consumes an amount e_i of energy for transmitting a unit of data. Suppose the network is expected to last for a duration of T.[1] Then, we have the power consumption constraint:

$$e_i \sum_{j:(i,j)\in L} f_{ij} \leq B_i/T, \quad i \in M. \tag{3}$$

As the network is energy-constrained, we want to minimize energy consumption as well as to balance energy consumption at different nodes. For this purpose, we assume that each node $i \in M$ incurs an energy cost $C_i(e_i x_i)$ when the total outgoing flow is x_i, which implicitly assumes that the transmission energy is dominant and the reception energy can be neglected. The cost function $C(\cdot)$ is assumed to be continuous, twice-differentiable, increasing, convex function. We can thus formulate energy-aware routing as the following cost minimization problem:

$$\min_{f_{ij}\geq 0} \quad \sum_{i\in M} C_i(e_i \sum_{j:(i,j)\in L} f_{ij}) \tag{4}$$

$$\text{subject to} \quad (1) - (3). \tag{5}$$

a) Distributed algorithm: Consider the dual to the primal problem (4)-(5):

$$\max_{p\geq 0, q\geq 0, h\geq 0} \quad D(p, q, h) \tag{6}$$

with the dual function

$$\begin{aligned} D(p, q, h) = \min_{f_{ij}\geq 0} \quad & \sum_i \{C_i(e_i \sum_{j:(i,j)\in L} f_{ij}) \\ & + p_i(\sum_{j:(j,i)\in L} f_{ji} + r_i - \sum_{j:(i,j)\in L} f_{ij}) \\ & + h_i(e_i \sum_{j:(i,j)\in L} f_{ij} - B_i/T)\} \\ & + \sum_{(i,j)\in L} q_{i,j}(f_{ij} - c_{ij}), \end{aligned} \tag{7}$$

where we relax the constraints (1)-(3) by introducing Lagrangian multipliers p_i, q_{ij}, and h_i. It will become clear later that p_i can be interpreted as node congestion price from the flow conservation, q_{ij} the link congestion price from the link rate constraint, and h_i energy price from the power consumption constraint.

The minimization problem in (7) can be decomposed into separate problems at each node $i \in M$:

$$\min_{f_{ij}\geq 0} \quad C_i(e_i \sum_{j:(i,j)\in L} f_{ij}) - \sum_{j:(i,j)\in L} f_{ij}(p_i - p_j - q_{ij} - e_i h_i). \tag{8}$$

The above link flow allocation problem (8) admits a unique maximizer, which adjusts the link flows for given price $u(t) = (p(t), q(t), h(t))$ at time t according to:

$$f_{ij}(u(t)) = [C_i'^{-1}(\frac{p_i(t) - p_j(t) - q_{ij}(t) - e_i h_i(t)}{e_i})]^+, \tag{9}$$

[1] T can be adjusted according to the current situation in a disaster area. More generally, each node i can choose a duration of T_i it expects to last.

where "+" denotes the projection onto the set $\mathcal{R}^+$ of non-negative real numbers.

Solving the dual problem (6) by the gradient method, we obtain the following algorithm for price adjustment at node $i \in M$:

$$p_i(t+1) = [p_i(t) + \gamma(\sum_{j:(j,i)\in L} f_{ji}(u(t)) + r_i - \sum_{j:(i,j)\in L} f_{ij}(u(t)))]^+, \quad (10)$$

$$q_{ij}(t+1) = [q_{ij}(t) + \gamma(f_{ij} - c_{ij})]^+, \quad (11)$$

$$h_i(t+1) = [h_i(t) + \gamma(e_i \sum_{j:(i,j)\in L} f_{ij}(u(t)) - B_i/T)]^+, \quad (12)$$

where γ is a positive stepsize. We see that the prices admit an economic interpretation: when the sum of total incoming flow and the generated flow is greater than the total outgoing flow, the node congestion price p will increase, and otherwise it will decrease; when the link flow is greater than the link data rate, the link congestion price q will increase, and otherwise it will decrease; when the energy consumption is greater than that budgeted for a duration of T, the energy price h will increase, and otherwise it will decrease.

The distributed algorithm (9)-(12) can be implemented online, and hence the price update (10)-(12) will be automatically carried out by the network dynamics in queue length and energy consumption.

b) Convergence: The algorithm (9)-(12) is a subgradient algorithm for convex problem (4)-(5). We can apply the result in, for example, [15], [16], to show that (9)-(12) will converge to the optimal of problem (4)-(5) and its dual, with appropriate choice of stepsize γ.

4) Downstream Data Forwarding: We adopt a simplified version of the upstream baseline routing in the downstream data forwarding process. Each node maintains downstream path ETN values (the weight of the currently-known shortest path) for nodes from whom it receives their upstream data packets.

Instead of proactively announcing its current downstream ETN values to all of its neighboring nodes, each node i only announces the downstream ETN of node k to a neighbor j, if it forwards packets originated from k to j. In the implementation, for every 100 packets originated from node k and forwarded from i to j, we attach i 's current downstream path ETN for node k in one of them as an extra field in the packet, in order to reduce overhead from control packets.

Each node i in the network also maintains a set of N_{ik} neighbors who have a closer shortest path to downstream node k. We then apply the energy-aware multi-path routing based on the converged connectivity graph for the flow control of the downstream data forwarding.

Admittedly, using reverse link of upstream routing for downstream data forwarding might not take full advantage of all of the available downstream communication resources, since the quality of wireless link is not always symmetric. However, we apply the energy-aware multi-path routing to optimize the data forwarding performance in the built downstream connectivity graph based on the considerations of complexity. The communication overhead for performing a proactive distance-vector routing algorithm is exponential to the number of nodes in the network, since a many-to-many connected graph needs to be built. Our simplified version of baseline routing builds a sub-graph during the upstream data forwarding process, without introducing significant communication overhead.

IV. Performance Evaluation

We implement the proposed low-complexity, energy-aware, multi-path routing algorithm in both NS-3 simulator and Android operating system. We perform packet-level simulations to evaluate the performance of the system in packet delivery ratio and delay, and carry out phone-in-the-loop emulations on actual Google Nexus devices to evaluate the energy efficiency of the hybrid cellular-MANET.

A. Algorithm Implementation

The baseline routing (Section III-B2) is implemented to construct an effective connectivity graph for the hybrid MANET. We estimate ETN of each link based on the probing procedure proposed by De Couto et al. [17], which considers packet loss and retransmission that is due to channel error and incorporates the effect of loss rate asymmetry between both directions of a link.

To implement the energy-aware multi-path routing, each node logically maintains a local sending queue for each link. The arrivals at these local sending queues are regulated by the corresponding link flows that are updated according to equation (9). The parameters used in the implementation are as follows: the stepsize γ is set to being proportional to $\frac{1}{n}$, with n the number of nodes in the hybrid cellular-MANET; the energy cost function $C_i(e_i x_i)$ is set to $\beta_i(e_i x_i)^2$, where β_i's are uniformly drawn from [0.2, 0.5]; and the amount e_i of energy for transmitting a packet at node i is sampled based on the number of packets sent and the change of the battery level that is obtained from the callback function of the mobile operating system. Based on preliminary experiments, we used $e_i = 0.00018$ percent of the total battery level in simulations.

To implement equation (10), each node i maintains a "node" queue, whose queue-length Q_i^p increases by 1 each time the node i receives a packet from any of its neighbors or generates a data packet itself and decreases by 1 each time the node i sends a packet to any of its neighbors (out of the local sending queues). The node congestion price can be calculated by $p_i(t) = \gamma Q_i^p(t)$ based on the measured queue-length.

To implement equation (11), each node i maintains a "link" queue for each outgoing link (i, j), whose queue length Q_{ij}^q increases by 1 each time the node i puts a packet in the local sending queue to node j and deceases by 1 each time the node i successfully sends a packet to node j. The link congestion price can be calculated by $q_{ij}(t) = \gamma Q_{ij}^q(t)$ based on the measured queue-length. Note that the packet-level implementations of f_{ij} are different for equations (10) and (11).

To implement equation (12), the initial battery level B_i and battery level $b_i(t)$ at time t are locally observed from the callback function of the mobile operating system at each node i. Suppose that the battery level is observed consecutively at times $\hat{t}$ and t. The energy price can be calculated by

$$h_i(t) = [h_i(\hat{t}) + \gamma(b_i(t) - b_i(\hat{t}) - \frac{t-\hat{t}}{T}B_i)]^+, \quad (13)$$

and initially $h_i(0) = 0$. We set $T = 4$ hours in simulations.

Finally, to implement equation (9), each node i periodically updates $f_{ij}(u(t))$ to control the link flow to node j. The link flow $f_{ij}(u(t))$ is emulated at packet level by releasing $\delta f_{ij}(u(t))$ packets to the corresponding local sending queue over the time interval of δt. δt corresponds to the duration of a time slot in the flow level algorithm (9)-(12), which decides the frequency at which a node reads $p_i(t)$ and $q_{ij}(t)$, calculates $h_i(t)$, and adjusts $f_{ij}(u(t))$ accordingly. When a node j receives upstream packets from its neighbor i, it will periodically send control packets to i, which contain its latest $p_j(t)$. By this way, node i will have all the necessary information to calculate $f_{ij}(u(t))$. In all the simulations, we set the stepsize $\gamma = 2/n$ and the duration of a timeslot $\delta t = 25ms$.

B. Android Prototype

We implement the proposed routing algorithm as an Android service that runs on the installed devices with a high priority. Mobile devices with Android 4.0 (and above) operating systems can install it without root privilege, and use it to form a hybrid cellular-MANET based on the built-in WiFi-Direct module. However, WiFi-Direct suffers from the scalability issue due to the inability of a device to serve as both a client and a virtual access point at the same time. We use CyanogenMod Rom with a kernel module support to enable WiFi ad hoc mode for large-scale hybrid cellular-MANETs.

In this Android service, a lower communication layer is built to implement the routing mechanism based on Android WiFi-Direct or WiFi ad hoc mode (for phone to phone communication), accelerometer (for mobility context inferring), and battery APIs (for energy-aware component). A higher service layer is implemented for providing APIs for other applications in the device. Applications that provide text messaging, social networking, and voice services are able to utilize the extended Internet access by making an inter-process call to the higher service layer. We use a Galaxy Nexus phone that installs this Android service in phone-in-the-loop emulations to evaluate the energy efficiency of the protocol.

C. Packet-Level Simulations

We perform packet-level simulations on the NS-3 simulator to evaluate the performance of the proposed routing algorithm. The nodes are equipped with both standard 802.11 WiFi ad hoc and LTE interfaces, and are randomly placed within a radius of 1000 meters. The average data rates r_i for the data generated at nodes i are uniformly drawn from [0, 1Mbps].

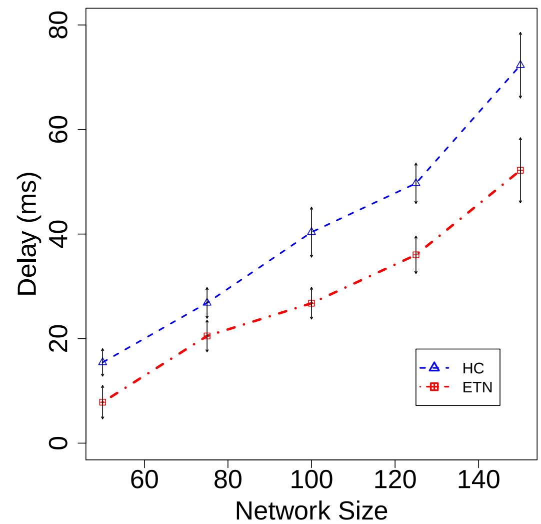

Fig. 2: End-to-end Delay Comparison Between HC-based and ETN-based Routing

1) Benefits of ETN: To evaluate the benefits of using ETN as the link quality metric, we randomly place nodes in the area using the same randomization seed, and vary the network size – 50, 75, 100, 125, and 150 nodes. We measure the end-to-end delay and packet delivery ratio (PDR) of our routing algorithm, and compare them with the classic hop-count (HC) based distance-vector routing algorithm. Both algorithms use multi-path and energy-aware components of our design. The only difference is that the former uses ETN as the link quality metric and the latter uses HC as the link quality metric. To utilize multiple available paths, each node in both algorithms probabilistically sends packets through them based on their current $f_{ij}(u(t))$ values. The 95% confidence intervals of collected data are plotted in Figures 2 and 3.

We see that, as expected, our ETN-based routing outperforms the classic HC-based routing in both delay and PDR. Moreover, as the network size increases, the delay and the packet loss rate of the HC-based routing increases at a faster rate than the ETN-based routing. HC-based routing is oblivious of the link quality and may end up with using paths with a small number of hops but a large number of packet losses and retransmissions. As the network grows larger, the paths become longer and the benefits of ETN are compounded.

2) Responsiveness to Mobility: To evaluate the performance of the locally reactive routing, the nodes are assumed to randomly pause, and then move toward a random location at a speed uniformly drawn from [0m/s, 1.5m/s]. We vary the pause time – 0s, 50s, 100s, 150s, 200s, and compare the PDR of the hybrid cellular-MANET with the locally reactive routing component enabled (ETNR) with that of the network with this component disabled (ETN). As in the above experiment, both protocols use multi-path energy-aware component of our design. The 95% confidence intervals of collected data are plotted in Figure 4. We see that the locally reactive routing

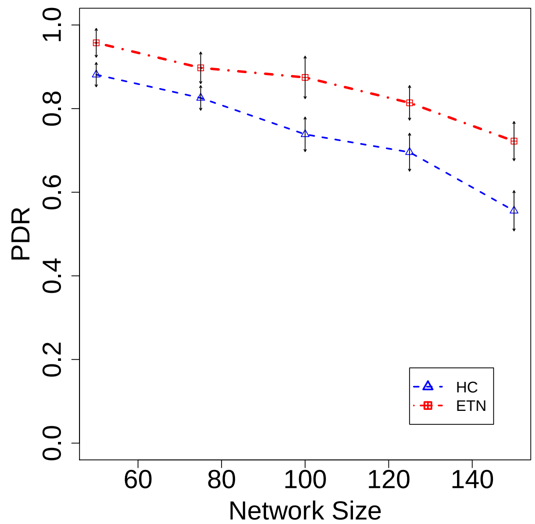

Fig. 3: Packet Delivery Ratio Comparison Between HC-based and ETN-based Routing

improves the PDR, which implies that it can effectively explore and exploit locally the links with better quality in a network with mobility.

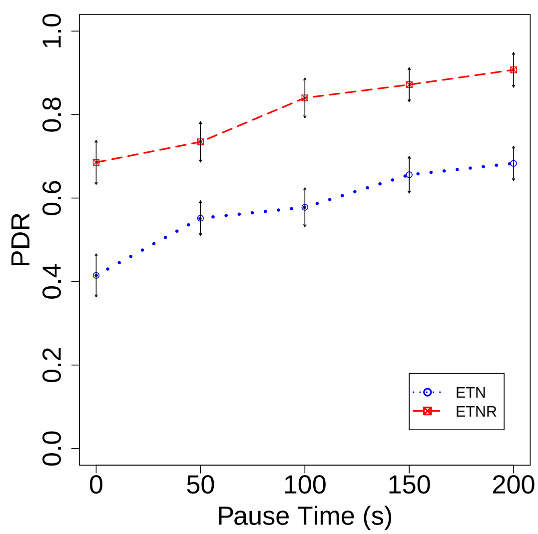

Fig. 4: Packet Delivery Ratio Comparison for Locally Reactive Routing

D. *Phone-In-The-Loop Emulations*

To evaluate the energy efficiency of our proposed routing protocol, we implement a phone-in-the-loop emulation testbed as described in Figure 5. We use a Google Galaxy Nexus phone that installs the hybrid cellular-MANET (HMANET) Android service described in Section IV-B to connect to the simulation server through its 802.11 WiFi ad hoc interface, i.e., “wlan” in the figure. The phone communicates with hosts in the Internet through its regular LTE interface, i.e., “cell” in

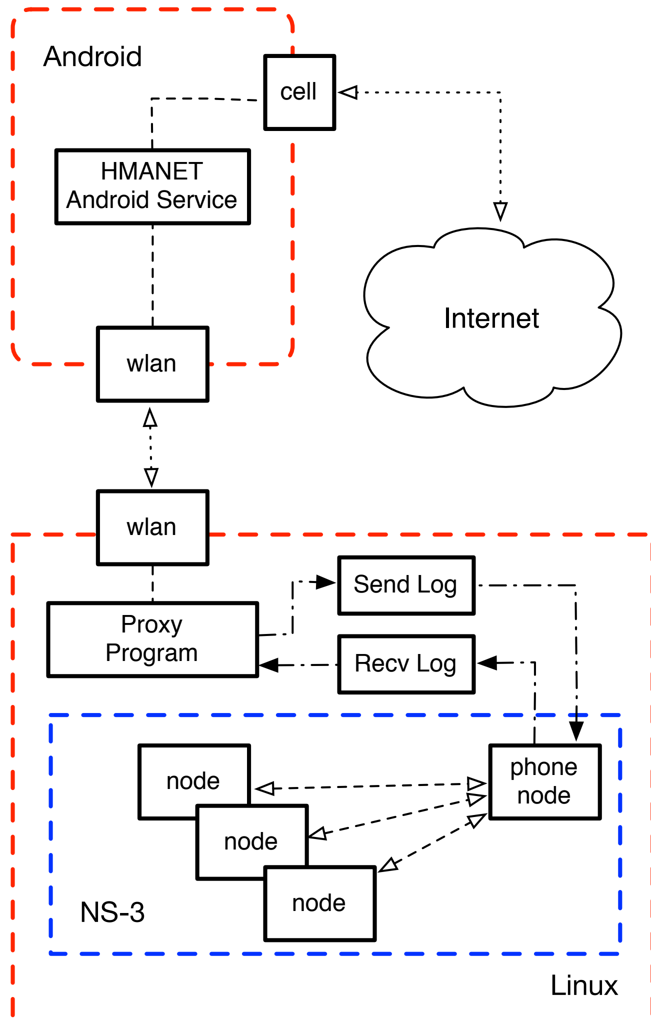

Fig. 5: Phone-In-The-Loop Emulation

the figure. There is a phone node in NS-3 that represents the phone and takes the responsibility of sending and receiving packets for the phone in the simulation. Basically this phone node is controlled by the actual phone, and thus cannot decide send and receive packets by itself. The behavior of the phone is governed by the low-complexity, energy-aware, multi-path routing control logic implemented in the installed HMANET Android service.

The communication mechanism between the phone and the simulation is implemented as follows: (1) once the phone node receives a packet, it notifies a proxy program on the simulation server through its local file system. The proxy program then forwards this packet to the phone through 802.11 WiFi ad hoc; and (2) once the phone needs to send a packet to other nodes in NS-3, it sends to the proxy program first. The program then notifies the phone node through the local file system. Finally, the phone node forwards this packet to other nodes in the simulation.

Admittedly, the ETN between the phone and the simulation machine might be smaller than the ETN in the simulation. To compensate this effect on energy consumption, we use the ETN value obtained from the simulation and make the phone send extra packets to another IP address through its 802.11 WiFi ad hoc interface.

The emulations are performed in real time for a hybrid cellular-MANET of 100 nodes, which travel randomly at a speed uniformly drawn from [0m/s, 1.5m/s] and with pause time 0s. We record battery traces over time, and compare the energy consumption of three routing schemes: (1) ETN: the ETN-based protocol with neither the reactive component nor the energy-aware component; (2) ETNR: the ETN-based protocol with the locally reactive component but without the energy-aware component; and (3) ETNRE: the full-fledged protocol with the ETN, the locally reactive, and the energy-aware component. All the three schemes use the multi-path component, and probabilistically sends packets based on the $f_{ij}(u(t))$ values of available paths. To disable the energy-aware component in ETN and ETNR, we use $h_i(t) = 0$ each time we update equation (9). The traces are plotted in Figure 6. We see that the energy-aware routing component can achieve more efficient energy consumption. Also note that ETNR consumes more energy than ETN, which is due to the fact that ETNR will consume a significant portion of energy in sending signaling/control messages in the locally reactive routing when the pause time is 0.

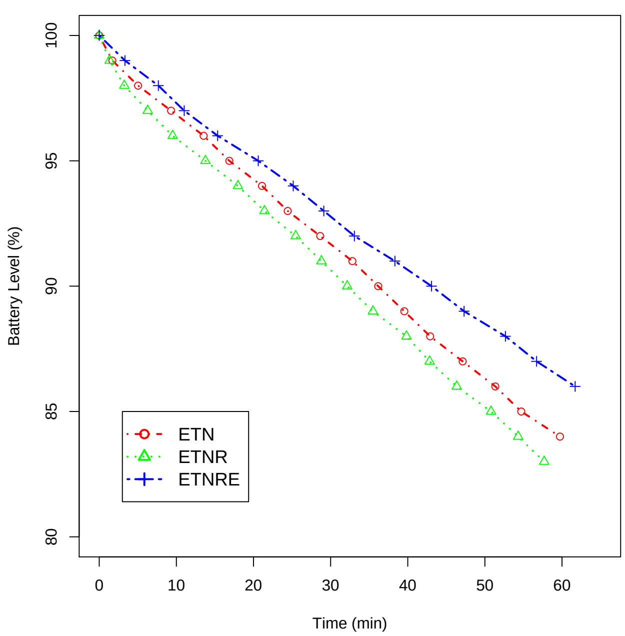

Fig. 6: Battery Consumption for Different Routing Schemes

V. Conclusion

We have presented a self-organizing communication framework for mobile devices in disaster areas to form a hybrid cellular-MANET to extend wireless coverage, without requiring the modification of the existing wireless infrastructure. We design a low-complexity, energy-aware, multi-path routing protocol for this framework. Packet-level simulations show that the proposed routing scheme achieves good performance in delay, packet delivery, and energy consumption. We have also implemented this framework on Android devices and conducted phone-in-the-loop emulations. The results from the emulation show that the proposed routing scheme can achieve more efficient energy utilization. In the future, we plan to extend the prototype with the Android devices into a full-fledged testbed for the hybrid cellular-MANET and have it tested with real users.

References

[1] J.-S. Huang, Y.-N. Lien, and C.-L. Hu, "Design of contingency cellular network," in *Network Operations and Management Symposium (APNOMS), 2012 14th Asia-Pacific*, Sep, pp. 1 – 4.

[2] G. O'Reilly, A. Jrad, R. Nagarajan, T. Brown, and S. Conrad, "Critical infrastructure analysis of telecom for natural disasters," in *Telecommunications Network Strategy and Planning Symposium (NETWORKS), 2006 12th International*, Nov, pp. 1 – 6.

[3] K. Cho, C. Pelsser, R. Bush, and Y. Won, "The japan earthquake: the impact on traffic and routing observed by a local isp," in *Proceedings of the Special Workshop on Internet and Disasters*, ser. SWID '11, pp. 2:1 – 2:8.

[4] Y. Ran, "Considerations and suggestions on improvement of communication network disaster countermeasures after the wenchuan earthquake," *Communications Magazine, IEEE*, vol. 49, no. 1, pp. 44 – 47, Jan 2011.

[5] C. Zheng, D. Sicker, and L. Chen, "Self-organized context-aware hybrid manets," in *Wireless On-demand Network Systems and Services (WONS), 2013 10th Annual Conference on*, pp. 128 – 130.

[6] C. Wijting and R. Prasad, "Evaluation of mobile ad-hoc network techniques in a cellular network," in *Vehicular Technology Conference, IEEE VTS-Fall VTC, 2000 52nd*, vol. 3, pp. 1025 – 1029.

[7] C. Cavalcanti, C. Cordeiro, A. Kumar, and D. Agrawal, "A new routing mechanism for integrating cellular networks, wlan hot spots and manets," in *Personal, Indoor and Mobile Radio Communications (PIMRC), 2005 IEEE 16th International Symposium on*, vol. 2, Sep, pp. 1414 – 1418.

[8] Y. Bai, W. Du, Z. Ma, C. Shen, Y. Zhou, and B. Chen, "Emergency communication system by heterogeneous wireless networking," in *Wireless Communications, Networking and Information Security (WCNIS), 2010 IEEE International Conference on*, Jun, pp. 488 – 492.

[9] M. Bahr, "Update on the hybrid wireless mesh protocol of ieee 802.11s," in *Mobile Adhoc and Sensor Systems (MASS), 2007 IEEE Internatonal Conference on*, Oct, pp. 1 – 6.

[10] T. Fujiwara and T. Watanabe, "An ad hoc networking scheme in hybrid networks for emergency communications," *Ad Hoc Netw.*, vol. 3, pp. 607 – 620, Sep 2005.

[11] C. Gershenson, F. Heylighen, and C. L. Apostel, "When can we call a system self-organizing," in *In Advances in Artificial Life, ECAL 2003 LNAI 2801 7th European Conference*, pp. 606 – 614.

[12] C. Prehofer and C. Bettstetter, "Self-organization in communication networks: principles and design paradigms," *Communications Magazine, IEEE*, vol. 43, no. 7, pp. 78 – 85, Jul 2005.

[13] B. Manoj and A. H. Baker, "Communication challenges in emergency response," *Commun. ACM*, vol. 50, no. 3, pp. 51 – 53, Mar 2007.

[14] L. Ravindranath, C. Newport, H. Balakrishnan, and S. Madden, "Improving wireless network performance using sensor hints," in *Proceedings of the 8th USENIX conference on Networked systems design and implementation*, ser. NSDI'11, pp. 21 – 34.

[15] L. Chen, S. H. Low, M. Chiang, and J. C. Doyle, "Cross-layer congestion control, routing and scheduling design in ad hoc wireless networks," in *Proceedings of IEEE Infocom*, April 2006.

[16] L. Chen, S. H. Low, and J. C. Doyle, "Cross-layer design in multihop wireless networks (invited)," *Special Issue on Wireless for the Future Internet, Computer Networks Journal*, vol. 55, no. 2, pp. 480–496, 2010.

[17] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," *Wirel. Netw.*, vol. 11, no. 4, pp. 419 – 434, Jul 2005.