Energy Efficient Ad Hoc Networking Devices for Off-the-Grid Public Safety Networks

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***Abstract*—In this paper, we present the preliminary work towards providing a complete end-to-end solution that can connect survivors of a disaster with each other and public safety authorities using a completely self-sufficient ad hoc network. Accordingly, we develop a Heterogeneous Efficient Low PowEr Radio (HELPER) that acts as a WiFi (Wireless Fidelity) access point for end-users to connect using custom application. These HELPERs then coordinate with each other to form a LoRa based ad hoc network. The proposed solution will use a distributed optimized cross-layer routing algorithm that aims to maximize the network lifetime. This aspect is critical especially in energy-limited scenarios after a disaster. Some of the envisioned services include text and voice messages, live map updates, ability to send distress messages (like 911 calls) to authorities. HELPER network can also be used by authorities to remotely monitor the connectivity of the affected area, alert users of imminent dangers and share resource information. We intend to provide resources (code and instructions) that will enable the researchers of the community to set up a HELPER in a cost-effective ($< \$150$) manner using commercial off-the-self components and advance it further. Overall, we hope this technology will become instrumental in improving the efficiency and effectiveness of public safety activities.**

***Index Terms*—emergency ad hoc network, cross-layer routing, energy efficient network.**

I. Introduction and Background

Natural and man-made disasters are undesirable but sometimes unavoidable. In these scenarios, one of the most critical infrastructure affected are often communication networks. Authorities such as Emergency Response Center (ERC) set up by agencies like Federal Emergency Management Agency (FEMA) is heavily reliant on wireless communication for information gathering, command and control. This imposes the need for the Emergency Responders (ERs) and affected individuals to be best equipped with wireless communication technologies to maintain connectivity even when the traditional infrastructures (like cell towers) are affected or unavailable. Several steps have been taken to enable wireless communication between ERs in such situations [1], [2], [3] with an objective to improve interoperability, reliability and accessibility. In comparison, there are few solutions designed to connect the affected survivors to the ERs and the ERCs [4], [5], [6]. Additionally, only a few solutions have been implemented and prototyped to establish feasibility [6], [4]. *There is a lack of portable, low cost, energy-efficient solutions that connect both ERs and End Users (EUs) without the need of a dedicated infrastructure.* Therefore, in this work, we focus on designing a solution (hardware and software) that can be deployed by civilians (in their households) and ERs (roadside or other locations) to establish infrastructure-less network that enables communication between EUs, ERs and ERCs during the aftermath of a disaster.

We recognize some of the key requirements for the proposed Heterogeneous Efficient Low PowEr Radio (HELPER) Network. Firstly, any solution that enables emergency communication must be self-sustained and scalable. Second, the solutions should be accessible to the EU such that there is no learning time to use the network. Third, energy efficiency is another critical requirement for such technologies as there might also be a shortage or absence of electricity during this period. Finally, the solution should be portable, easy to deploy and cost effective. Accordingly, in this paper, we describe the preliminary design towards development of a HELPER for enabling emergency ad hoc network. The proposed end-to-end ad hoc networking solution will be capable of establishing an independent, low cost, low power wireless network for off-the-grid users during the aftermath of a disaster. One of the objectives of this work is to restrict the cost of the proposed device as much as possible such that each household can have one in their emergency kit and easily set it up when other communication infrastructure is disrupted. These HELPERs will form a wireless ad hoc network connecting users among themselves and to the ERs and ERCs. The overarching goal of the HELPER network is to provide limited key services like text and voice messages within the neighborhood, ability to share resource information (water, food, gas, and internet) and ability to send distress messages to the ERC. On the other hand, the ad hoc network will also be used by the ERC to remotely monitor the connectivity of the affected area and send alerts regarding imminent dangers to the connected EUs.

II. HELPER Prototype Hardware Design

The current prototype is shown in Fig. 1. The main board used is a Raspberry Pi (RPI) 3b. The choice was motivated from the low cost, size and large open community support for RPI development. Additionally, it is enabled with (Wireless Fidelity (WiFi) 802.11 b/g/n) and will be setup to operate as an access point for EUs. Since WiFi is not ideal to setup large area networks due to its limited coverage, we choose LoRa [7] to setup low power, long range links (2-5 km in urban areas and 15 km in suburban areas) between HELPERs. LoRa is emerging as a viable communication choice for Internet of Things (IoT) devices that strive to operate at low power yet achieve long ranges. A Global Positioning System (GPS) receiver is also attached to the RPI. This will be used to acquire

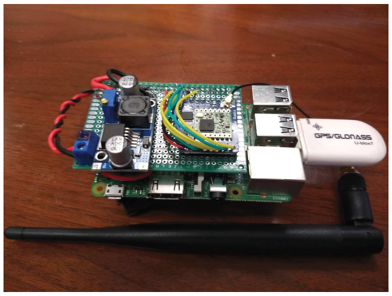

Fig. 1. HELPER Prototype

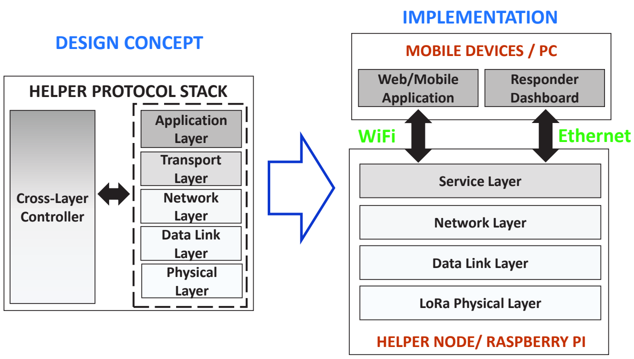

Fig. 2. HELPER's cross-layer Protocol stack design and implementation

the location information to perform geographical routing and to indicate the location of the node when assistance needs to be dispatched. We use two lightweight, 3000 mAh 18650 Li-Ion batteries as a power source. With the estimated load of ~ 1 Wh from the device, two batteries that supply around 22 Wh, the ER devices will be operable for a total of at least 8-9 hours before needing to be recharged/replaced. Since existing techniques like LoRaWAN is designed for centralized operation, we propose a novel cross-layer that aims to maximize the network lifetime to mitigate the formation of network holes.

III. HELPER'S CROSS-LAYER PROTOCOL STACK

The significance of cross-layer optimization in wireless communication under such resource constrained scenarios has been widely studied [8], [9], [10], [11] across various domains. Recently, there has been some substantial work [12], [13] in developing cross-layer platforms to avail the advantages of cross-layer optimization. Figure 2 depicts the design concept of a HELPER and how the design is currently implemented in a modular manner on the selected platform. Due to lack of space, we do not discuss these layers in depth rather try to convey the main role of each layer.

1) Physical Layer: HELPER is enabled using two wireless technologies WiFi (802.11 b/g/n) and LoRa which gives it the heterogeneous nature of operations. The prominent reason behind using both these well established wireless technologies are as follows, (i) WiFi is ubiquitous in today's devices and this will ensure familiarity and seamless access for EUs, (ii) LoRa is becoming a prominent communication technology enabling IoT devices that require low power, long range wireless links and (iii) it is extremely cost effective to use off-the-shelf physical layer to ensure low Size, Weight, and Power (SWaP).

2) Data-Link Layer: One of the primary function of the data-link layer is negotiating the medium access. We have implemented a similar Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) based Medium Access Control (MAC) protocol to setup multihop ad hoc network using LoRa. The data-link layer shown in Fig. 2 contains the control logic used by HELPERs to negotiate access of the wireless medium. It houses the Finite State Machine (FSM) used to implement the CSMA/CA like MAC protocol used by the HELPER network. Each of these control packets (RTS, CTS, BEACON) carry information including, instantaneous backlogged queue length, residual energy, location and the observed goodput per neighbor, which we refer to as Optimization Assisting Information (OAI).

3) Network Layer: To ensure scalability and to maximize network lifetime, we propose a novel cross-layer routing algorithm. Consider a dense multihop wireless ad hoc network comprised of several N HELPERs (which we refer to as nodes in this section) modeled as a directed connectivity graph $\mathcal{G}(\mathbb{N},\mathbb{E})$, where $\mathbb{N} = \{H_1, H_2..., H_N\}$ is a finite set of wireless transceiver (nodes), and $\mathfrak{L}(i,j) \in \mathbb{E}$ represents unidirectional wireless link from node H_i to node H_j (for simplicity, we also refer to them as node i and node j). We assume $\mathcal{G}$ is link symmetric, i.e., if $\mathfrak{L}(i,j) \in \mathbb{E}$, then $\mathfrak{L}(j,i) \in \mathbb{E}$. Each node is assumed to have the transmission range R based on the chosen transmit power P_t. All the nodes are equipped with GPS and therefore the location (longitude/latitude) coordinates are known. The knowledge of node locations is important for geographical/position based routing algorithms proposed in this work. Let us denote the set of neighboring nodes of node i as $\mathbb{N}_i = \{j,k\}$ and the sink (ERC) node as s. The location of s can be predefined in every node or as in our case, this information is flooded at the time of network setup. In this formulation, we consider packets that has to be transmitted from node i to sink s but this can be extended to any source-destination pair.

The distance between any two nodes i and j is represented by d_{ij}. If a node j exist within the transmission range of node i, there exists a link $\mathfrak{L}_(i,j)$, i.e., a wireless communication link $\mathfrak{L}_(i,j)$ exists when $d_{ij} \leq R$. The power consumed over $\mathfrak{L}_(i,j)$ or the power required by the source node (i) to transmit to a neighboring node (j) is denoted by $\mathtt{P}_{ij}$. The initial and residual battery energy at node i can be denoted as $\mathtt{E}_0^i$ and $\mathtt{E}_r^i$ respectively. Every node maintains a queue that holds the outbound packets. Let $\mathtt{q}_i$ represent the instantaneous number of packets retained in the queue of node i, also called the queue backlog. The transmission bit rate and Bit Error Rate (BER) over $\mathfrak{L}_(i,j)$ are denoted by R_b^{ij} and e_b^{ij} respectively.

Each node in the proposed distributed energy efficient backpressure routing algorithm utilizes the following parameters associated with potential next-hop; (i) proximity to sink, (ii) differential queue backlog, (iii) residual battery energy, (iv) power required to transmit over the link and (v) the corresponding link throughput. This information is gathered from traditional control packets like RTS, CTS and BEACON packets. As discussed earlier, these packets will contain updated OAI and a PROBE field. The PROBE field would contain a bit sequence known by the nodes in the network which is used to compute effective throughput (bps). The energy efficiency of a given link can be expressed as a ratio between goodput (G_{ij}) and transmission power (P_{ij}) as [14],

$$\eta_{ij} = \frac{\mathrm{R}_b^{ij}\left(1-\mathrm{e}_b^{ij}\right)}{\mathtt{P}_{ij}} = \frac{\mathrm{G}_{ij}}{\mathtt{P}_{ij}} \tag{1}$$

where η_{ij} gives the measure of number of bits successfully transmitted over $\mathfrak{L}_(i,j)$ per Joule of transmission energy. Another key factor that needs to be considered in routing is the differential queue backlog ($\Delta\mathcal{Q}_{ij} = \mathtt{q}_i - \mathtt{q}_j$) with respect to the source node (i) and next-hop (j) [15], [16]. Considering the queue backlog is necessary to mitigate congestion in the network and traditional backpressure algorithms has been shown to be throughput optimal [15]. The effective progress made by a packet can be represented as $d_{is} - d_{js}$. Choosing nodes that provide larger progress implies fewer hops to the sink node which in turn could lead to smaller energy consumption. Finally, to ensure uniform depletion of energy per node, we need to consider the $\mathtt{E}_r^j$ of potential next hops. Therefore, we define our utility function as follows,

$$\mathcal{U}_{ij} = \eta_{ij}\left(\frac{\max\left[\Delta\mathcal{Q}_{ij},\epsilon\right]}{\mathtt{q}_i}\right)\left(\frac{d_{is}-d_{js}}{d_{is}}\right)\left(\frac{\mathtt{E}_r^j}{\mathtt{E}_0^j}\right), \forall j \in \mathbb{NB}_i \tag{2}$$

where ϵ is a very small constant to avoid negative values. The objective of the network is to maximize the summation of $\mathcal{U}_{ij}$ for all possible links $\mathfrak{L}_(i,j)$ in order to maximize the overall energy efficiency of the network. This in turn will ensure reliable communication while maximizing the network lifetime (which is defined as the time when first node in the network depletes its energy leading to a network hole). The optimization problem is subject to residual battery energy, queue backlog, bit error rate and capacity constraints. This is formulated as Problem $\mathcal{P}_1$ shown below,

$$\begin{aligned} \mathcal{P}_1: \text{Given}&: \mathcal{G}(\mathbb{N},\mathbb{E}),\ \ \mathbb{G},\ \ \mathbb{E}_r,\ \ \mathbb{Q} \\ \text{Find}&: \mathbb{NH}^*, \mathbb{T}^* \\ \text{Maximize}&: \sum_{i\in\mathbb{N}_{net}}\sum_{j\in\mathbb{NB}_i}\mathcal{U}_{ij} \end{aligned} \tag{3}$$

subject to:

$$\mathrm{R}_b^{ij} \le C_{ij},\ \ \mathrm{e}_b^{ij} > \mathrm{e}_{b*}^{ij},\ \ \forall i \in \mathbb{N}_{net},\ \forall j \in \mathbb{NB}_i \tag{4}$$

$$\mathtt{E}_r^i > 0,\ \ \mathtt{q}_i \ge 0,\qquad \forall i \in \mathbb{N}_{net} \tag{5}$$

where the objective is to find the set of next-hops and transmission strategy for all nodes in the network which can be represented as $\mathbb{NH}^* = [\mathrm{NH}_i^*]$ and $\mathbb{T}^* = [\mathrm{T}_{ij}^*]$ respectively, $\forall i \in \mathbb{N}\ j \in \mathbb{NB}_i$. In the above optimization problem $\mathcal{P}_1$, $\mathbb{G} = [\mathrm{G}_{ij}]$, $\mathbb{E}_r = [\mathtt{E}_r^i]$ and $\mathbb{Q} = [\mathtt{q}_i]$, $\forall i \in \mathbb{N}_{net}$, $\forall j \in \mathbb{NB}_i$ denote the set of goodput measure, residual battery energy and queue backlogs respectively. The constraints in (4) restrict the total amount of data rate in link (i,j) to be lower than or equal to the physical link capacity and impose that any transmission should guarantee the required BER. Constraints (5) ensure the residual energy and queue backlog of each node will not have negative values. It can be seen that for solving the above optimization problem nodes would require global knowledge of the network. Since the centralized optimization method is not a scalable solution, it motivates the need for a scalable distributed solution. To enable distributed operation, each node with a packet to transmit choses an optimal next-hop and transmission parameters such that it maximizes its own local utility function. This can be considered as a divide-and-conquer approach to solve the optimization problem in a distributed manner. Accordingly, every source node (i) will aim to maximize the utility function $\mathcal{U}_{ij}$ and select the optimal next-hop and transmission strategy as follows,

$$[j^*, \mathrm{T}_{ij}^*] = \arg\max_j \mathcal{U}_{ij}, \forall j \in \mathbb{NB}_i \tag{6}$$

4) Service Layer: The Service Layer provides a common interface between HELPER applications and the lower layers of the protocol stack. This layer communicates to HELPER applications using local sockets and the Network Layer via direct function calls. Messages received from applications are translated from HELPER Send format to HELPER Packet format and are passed to the network layer. Messages received from the network layer are translated from HELPER Packet structure to HELPER Receive format and are then passed to the application. In implementation, the Service Layer uses an MQTT messaging socket to communicate with the Web Application and messages are encoded using JSON. The Paho MQTT CPP and Rapid JSON libraries are used to implement the messaging to the application. The implementation is such that more application message types and message handling can be added in future to expand the capabilities of the HELPER network.

5) Applications: As discussed earlier, to provide a complete end-to-end solution, we have developed two applications one for EU to connect to the HELPER network using their mobile devices and the second for ERC to remotely monitor the network and provide assistance and alerts to the EU. In this section, we describe the functionalities that has been enabled through these applications.

Every user connected to a HELPER via WiFi will be prompted to access the services of HELPER network by logging in to the custom Website Application (Web App) (shown in Fig. 3) developed by us. As you can see, the page consists of the location of the HELPER (marked using a black marker) that the user is currently connected to and the neighboring HELPERs in its vicinity are indicated on the map by blue markers. The primary goal of the HELPER Network is to keep individuals in the affected community connected and hence you can see various chat options. The users can select appropriate tab or option from pop up menu. Using *Local* tab, messages are exchanged between users connected to the same HELPER. These messages go directly over WiFi and do

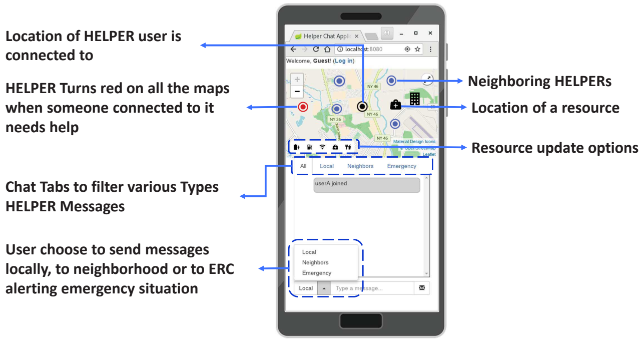

Fig. 3. Website Application

not need to interact with the LoRa physical layer. Next, the message send using *Neighbor* tab are broadcasted to h-hop neighbors (where h is predetermined by the designer). The choice of h would be a trade-off between energy consumption and range of connectivity. In this case, a message sent by EU to the neighbors are received by all EUs connected to all the HELPERs (black and blue markers) within h hops from the source HELPER. Most importantly, the *Emergency* tab is used to send distress messages directly to the ERC to seek help during distress. These messages will be carried over a multi-hop path and inform the ERC of the location where help is required. This serves as an alternative to 911 calls when the degradation of infrastructure renders traditional 911 calls infeasible.

A regional map with live updates on availability of resources like gas stations, operational hospitals, food and water, gas station, internet access, electricity etc are accessible to the connected users. The ERC will collect information about the availability of resources using HELPERs deployed in hospitals, stores, gas stations, households etc. Periodically, this information is flooded by the ERC in the ad hoc network to update the map at each HELPER. The periodicity of this flooding can be controlled by the ERC based on the update information and status of the network. It can be argued that the above three-step process may incur delay in disseminating information as compared to the information being flooded by the source HELPER itself without going through the ERC. While this may be true, authorizing any node to update resource information may lead to propagation of misinformation, duplicate information and overall larger energy consumption.

As shown in Fig. 2, at the ERC, a HELPER is connected to a PC using an Ethernet cable. ERC Dashboard (not shown due to lack of space) enables remote monitoring that allows controllers to discover all active HELPERs. Similar to the Wireless Emergency Alerts (WEA) that is used over the cellular network, the *ALERT* message is intended to inform every connected user about an imminent threat like high winds, rising water level, flash flood, fires etc. This message will also be distributed using an efficient flooding technique. Every user connected to a HELPER sees a message labeled from ERC and are therefore aware of the steps to remain safe during the upcoming situation. This will be beneficial in situations where cellular network is inoperable due to damage and large number of individuals need to be informed about imminent dangers.

IV. Conclusion

In this work, we have introduced a complete end-to-end solution that can be set up to maintain connectivity during the aftermath of a disaster. We have proposed a novel distributed, cross-layer routing protocol that aims to maximize the network lifetime. We have currently developed the hardware prototype and established multi-hop text messages using the custom developed application. We are currently performing extensive evaluation of our six node HELPER network and hope to publish results, demonstration videos and codes in near future.

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