Using Open-source Hardware to Support Disadvantaged Communications

Andrew Weinert, Hongyi Hu, Chad Spensky, and Benjamin Bullough
MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02420-9108
{andrew.weinert,hongyi.hu,chad.spensky,ben.bullough}@ll.mit.edu

***Abstract*—During a disaster, conventional communications infrastructures are often compromised, which prevents local populations from contacting family, friends, and colleagues. The lack of communication also impedes responder efforts to gather, organize, and disseminate information. This problem is made worse by the unique cost and operational constraints typically associated with the humanitarian assistance and disaster relief (HADR) space. In response, we present a low-cost, scalable system that creates a wide-area, best-effort, ad-hoc wireless network for emergency information. The Communication Assistance Technology over Ad-Hoc Networks (CATAN) system embraces the maker and do it yourself (DIY) communities by leveraging open-source and hobbyist technologies to create cheap, lightweight, battery-powered nodes that can be deployed quickly for a variety of operations. CATAN enables geographically separated users to share information on standard interfaces, i.e. web and SMS, over commonly-used communication interfaces, i.e. GSM and Wi-Fi. These interfaces enable CATAN to accommodate a variety of digital devices while leveraging the global ubiquity of cellular devices. By emphasizing simple, mature, technologies, CATAN avoids many problems that hinder many general purpose ad-hoc technologies. We have tested our infrastructure in a variety of environments and have open-sourced the entire project to encourage collaboration with the greater HADR community.**

I. Overview

During a natural disaster or regional crisis, communications are often compromised at the affected location. The ability to communicate in any environmental condition is crucial because communications enable safe and effective incident and humanitarian assistance and relief (HADR) response. It has been recognized that an effective response must be supported by a broad coalition of international, regional, and local actors [1], such as emergency managers, civic leaders, responders, non-government organizations (NGOs), and the public. Coordinating efforts across these actors requires timely, reliable and effective modes of communication. As the scale of an incident or disaster grows, the communications infrastructure must also adapt to support an increased number of responders, jurisdictions and systems across vast geographic areas. Deficiencies in capacity, interoperability or infrastructure can strain or overwhelm response capabilities; all of which are exacerbated during large-scale incidents.

Web-based services and communities operating in the cloud have transformed response [2]. However, there is frequently a disconnect between the realities the information systems at the affected location and those in the ubiquitous cloud. Internet enabled web technologies such as crowdsourcing [3] and social media [4] have helped facilitate interaction across these actors, but fail when communications at the affected region are either degraded or nonexistent due to either natural or human actions. For example, an estimated three million people were without cellular service immediately following the Haiti Earthquake (2010) [5]. Similarly, cellphone networks were overwhelmed in the moments after the 2013 Boston Marathon bombings [6]. This effectively disconnects the people in the affected region from the rest of the world (e.g., their families, responders); making it difficult to supply the web-based services with the information that subsequently provide data products to responders in the field.

Network repeaters and deployable infrastructure can be leveraged to address the gaps in network coverage and enable greater availability of response technologies, which improves overall situational awareness and the effectiveness of response planning [7]. However, existing technologies and research prototypes do not provide an end-to-end solution, i.e. re-establish communication networks, collect information from the affected area, and share that internet at a reasonable cost.

Over the past ten years, various research efforts have explored the potential of deployable communication assets [8]–[11]. Recently, some efforts have prototyped low-cost, small size, weight, and power (SWaP) communication solutions that leverage free and open-source software (FOSS) [12], [13]. These prototypes are designed to be concept of operations (CONOPS) and data agnostic and are not ideal for data collection and aggregation. Not leveraging these CONOPS and known information needs limits their robustness and does not address specific response needs, such as prioritization.

Additionally the logistics of HADR operations are often stressed [14], reducing the availability and utility of airborne sensor and communication assets. These assets can also be cost-prohibitive. Finally, while satellite communications are a viable method for the re-establishing general-purpose communications, they too are typically prohibitively expensive [15].

To address this capability gap, we leveraged design principles from previous disconnected, interrupted, and low-bandwidth (DIL)-focused prototypes, but with an emphasis on reliability, robustness, and compatibility. The Communication Assistance Technology over Ad-Hoc Networks (CATAN) pro-

This work is sponsored by the Department of the Air Force under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and not necessarily endorsed by the United States Government.

totype meets these design goals by embracing the maker and do it yourself (DIY) communities and leveraging open-source and hobbyist technologies to create rapidly deployable, cheap, lightweight, battery-powered units. CATAN enables efficient gathering and processing of information in the field as well as the ability to relay this data to already established services.

II. Needs and Assumptions

Disasters that require HADR response often experience infrastructure outages that destabilize the communication environment. These outages hinder collaborative command and control across all participating response agencies and impair the ability to collect, process, and distribute accurate information from disparate systems and platforms [16] in a timely manner. Understanding and designing for these conditions is paramount to the success of any technology.

The operating environment in a disaster scenario is likely to be affected by physical phenomena (e.g., roads, infrastructure, power) as well as the availability and distribution of communications technologies (e.g., phones, computers) to the affected people and responders.

1) Physical Environment: In general, a DIL communication environment can be the result of compromised infrastructure, a remote location with limited communications, or network saturation. The Federal Communications Commission (FCC) published a report on deployable communication opportunities for restoring critical communication infrastructure, which defines the characteristics of a worst-case operating environments [17]. The report predicts a near complete failure of all conventional communication platforms where access to roads and bridges may be impassable, thus preventing the transport of fuel and generators. Furthermore, some operating environments may have complex geometries that make it difficult to identify precise communication conditions [18].

While bleak, the FCC report accurately describes the environments experienced in major catastrophes the past five years, ranging from Haiti (2010) to Nepal (2015). For example, Hurricane Sandy (2012) knocked out 25% of cell towers in its path and required operational towers to run on backup generators [19]. Thus, in our design we have ensured that our units are small enough to be air-dropped, or potentially constructed within the affected region. The potential deployment on small drones or balloons were also explored.

2) Communications Technology: To understand the needs and requirements of our front-end communications interface, which is used to interact with the affected people and responders, we attempted to identify available consumer communications technologies that were used in various disasters. We used the Nepal Earthquake (2015) and Typhoon Haiyan (2013) as disaster use cases and the United States's population as a baseline for potentially affected individuals. In both of these disasters, mobile phones were heavily used. After the Typhoon Haiyan (2013) impacted the Philippines, it was reported that only feature phones were able to connect to the remaining cellular networks for some areas [20]. In Nepal, 86% of the population had mobile phones, and 30% could access the internet [21]. Although the United States has a vastly different economy, mobile phone usage is similar; 90% of American adults owned a cell phone in 2014 [22]. Furthermore, unlike Nepal, 64% of American adults own a smartphone, which also have internet capabilities. To this end, data-based interfaces such as IEEE 802.11 Wi-Fi are not necessarily sufficient; simpler technologies, such as short message service (SMS) [23], are also required.

Amateur radio technology was also used to help coordinate response efforts after the Nepal earthquake [24]. To maximize our coverage, we designed our system to be easily adapted to support numerous communication interfaces and modalities.

A. Bandwidth Environment Assumptions

We also needed to select an appropriate backend communications technology to support the numerous types of data exchanged in disaster scenarios. The technology must also meet the needs and priorities of the local actors from the effected region. Locating specific family members and identification of the dead are prioritized differently across cultures [25]. In Nepal (2015), for some local Nepalese organizations, locating their family members was the highest priority. Data collected for this mission was then leveraged to support other missions, such as infrastructure or damage assessment. Designing for this contextual information ensures robustness and the timely delivery of information in ad-hoc networks [26].

Table I shows a baseline of common activities and their data requirements. Note that most of the activities do not have significant bandwidth requirements. For example, simple text-based activities such as email, GPS coordinates, and SMS can easily operate with less than 1 Mbps of bandwidth.

While the data itself is not bandwidth intensive, the communication network could be bandwidth limited. An NGO responding to the Nepal Earthquake (2015) claimed that "[w]ithout question, bandwidth limitations are the single greatest problem..." Field teams typically operated with less than 0.5 Mbps of bandwidth to the internet, for up to ten days after the earthquake. In this environment, a typical 0.75 MB website would take at least 12 s to load with significant latency problems.

This highlights the need for a robust communication solution capable of maximizing limited bandwidth and with the ability to operate independently, i.e. without an internet connection. Any system requiring a persistent cloud-accessible connection is likely to fail in disaster scenarios. While the service should be able to eventually sync with internet-connected services, when a connection exists, this intermittent connectivity must be accounted for in the design. Similarly, the architecture should support network-aware services to continuously assess the network's configuration, health, and

TABLE I: Average Size of Potential Data Sources by Usage [15]

Activity	Megabytes	Megabits
Text only email	0.02	0.16
Average web page	0.75	6
Half hour of navigation directions	2.5	20
One photo	5	40
800 tweets [27]	9	72
One hour of video	500	4000

bandwidth availability to intelligently connect users, services, and devices.

To identify the state of affected individuals, we require a means of obtaining their vital information, a system for processing those details, and a means of communicating that data to others. Some of the world's most vulnerable individuals are internally displaced people (IDP), who have been made homeless by incidents or disasters. In 2011 alone, there was over 14 million new IDP due to natural disasters [28].

Google Person Finder [29] has recently become the de facto internet aggregation system used by the HADR community. Person Finder is a complete digital solution for collecting, processing, and communicating people's state information to others. Other systems for re-connecting people in affected regions include the International Committee of the Red Cross (ICRC) Family Links program [30], which provides online tracking of individuals, and Facebook's Safety Check [31], which similarly enables users to report that they are safe.

For disasters such as the Haiti Earthquake (2010) or the Japanese Tsunami (2011), Google Person Finder tracked over 50,000 and 616,000 records respectively [32]. Less than two weeks after the Nepal Earthquake (2015), more than 7,000,000 people were marked as safe using Facebook's Safety Check service [33]. Weeks after the Nepal disaster, Google Person Finder and the ICRC were tracking 8600 and 1120 records respectively. However, these systems are not always deployed for all incidents and disasters, and are heavily reliant on internet connectivity.

Google Person Finder and similar services store individuals' information in formats based on the People Finder Interchange Format (PFIF) model [34], an open standard extended from XML. The PFIF 1.4 data model has a 39 potential string based fields with only 8 required. Note that imagery are designated with a URL, not the raw image. Additionally, the United States Coast Guard search and rescue operations also leverage text-based message alerts [35]. Hence, a person's state can be characterized with text, requiring minor bandwidth.

B. Survivors' Technology

The democratization of technology through the DIY and hackerspace movements [36] as well as the rise of modern web-based technologies have both encouraged user collaboration within the HADR community. HADR response is no longer exclusively a government or NGO activity. Survivors and local actors have become an important component to any response [3]. Systems designed for DIY and FOSS enable technology that both disaster survivors and local actors can build and deploy with little external assistance.

The implementation of existing standards and technologies to support interoperability has enabled multi-organization collaboration and the support for diverse CONOPS. We emphasize that communication interoperability is critical for HADR because of the large number of organizations that are often involved in disaster response.

C. Design Objectives

Our system was designed with the following goals in mind: low cost, interoperabile, mobility, and SWaP (refer to Table II). We feel that CATAN meets these objectives, while providing a simple and robust platform to support a wide variety of operational environments and conditions. The low SWaP enables deployment on a variety of platforms from (e.g. small drones, masts, or in a backpack). Additionally, CATAN is non-proprietary, to encourage open-source collaboration and continued development. Historically, users and hobbyist groups, such as the active amateur radio community, have been a great resource for the development of new technologies and concepts, and we hope to facilitate their efforts. Fostering an open design should also help maintain a vendor-agnostic vision and limit the potential of proprietary components breaking certification or interoperability standards.

TABLE II: Design Objectives

Attribute	Design Objective
Cost	Base system less than $1000
Development	Must be open-source to enable community development
Fabrication	Assembled by a minimally skilled individual
Interoperability	Compatible with multiple data sources and organizations
Mobility	Easily and rapidly deployable within 15 minutes
Power	8+ hour endurance
Robustness	Acceptable for outdoor use
Size	Must fit in a backpack
Weight	3–5 lbs

III. CATAN PROTOTYPE

CATAN is designed to provide emergency communication services using a mesh of portable communication nodes. Each node provides front-end services for submitting and querying data, which end-users interact with using one or more front-end radio technologies (i.e. Wi-Fi or GSM). Each node also incorporates a back-end radio service, which is used to transmit and synchronize data between nodes. A central computing device ties the front and back-end links by performing several tasks, including: collecting and storing data; responding to user requests; and routing traffic between nodes (see Figure 1). Any node in the mesh that has internet connectivity will periodically, and automatically, upload newly received data to an online repository, such as Google Person Finder. Section V assesses if the prototype meets the design objectives.

A. Architecture

CATAN is designed to use commercial-off-the-shelf (COTS) components and be modular to minimize cost and allow integration of new future technology. For our prototype, we used Raspberry Pi (Model B+) single-board computers running the Raspbian Linux distribution for the central control units. The core CATAN services are written in Python and data is stored in an SQLite database. The front-end web interface is written in PHP, Python and JavaScript and served using the Apache webserver. The Google Map Javascript API [37] provides a geospatial component to the front-end interface.

The core software services are loosely coupled with the front and back-end services. The front-end Flask-based web service reads data from the SQLite database to respond to user queries. A Python script sends newly submitted data to the core CATAN service via a local socket, which allows a single server process to handle all database updates. A basic website written in Javascript and HTML can then be deployed on the CATAN node to provide a front-end interface for any end-user services.

The back end datalink is integrated by extending abstract base classes for the transmitter and receiver. Class instances are passed to the CATAN services using the pattern of dependency injection (or inversion of control). Therefore, any radio can be integrated into the system by implementing the *send* and *recv* methods of a transmitter and receiver sub-class to communicate with the specific datalink interface.

B. Front-end Radio Interfaces

CATAN is designed to interoperate with the wireless communication devices that might be available to survivors of a disaster. The prototype has been designed to provide service over Wi-Fi and GSM and be flexible enough for other services.

Each node includes a Wi-Fi radio operating as a wireless access point (AP). Users can use their wireless device to connect the AP, as they would any other publicly accessible Wi-Fi network. CATAN has also been designed to provide a limited set of GSM services by integrating an OpenBTS GSM base station. Once connected, a user will be automatically redirected to the locally hosted CATAN web application using DNS redirection or general packet radio service (GPRS) data services. The local web application prompts the user to enter her identifying information and status, which links that identity to the device. The user is able to query for the status of other individuals, create records requesting information about others and to provide status updates for her or other individuals. Finally, an SMS application allows a user to enter status information via an automated text-message dialog.

C. Back-end Radio Services

CATAN is designed to be agnostic to the back-end datalink used to communicate between peer nodes. We have integrated our prototype system with two different backend datalinks, and the initial prototype assumes that a particular network of nodes uses a single datalink at a time. Typical messages are less than 500 bytes, and pictures can be compressed to a few Kilobytes.

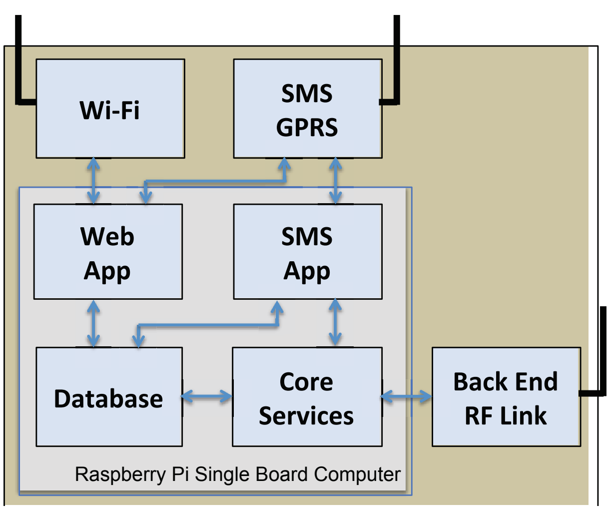


Fig. 1: CATAN System Architecture

The first back-end datalink uses User Datagram Protocol (UDP) packets over a peer-to-peer Wi-Fi mesh network. The mesh network is implemented using Ubiquiti Rocket M2 Wi-Fi radios. The radios are updated with FOSS firmware from the Broadband-Hamnet project, enabling operation as a peer-to-peer network. The firmware is further augmented with software that allows flooding of broadcast packets across the network.

The second back-end datalink uses very high frequency (VHF) radios that communicate using unnumbered AX.25 frames [38]. This was inspired by the Automatic Packet Reporting System (APRS), which has been used for many years by amateur radio operators to exchange short status messages across a peer-to-peer network of stations. Previous research [12] concluded that transmitting at related frequencies even in heavily treed environments result in coverage extending beyond one mile. While VHF and APRS system maybe considered dated technology, they can still provide significant utility due to frequency penetration.

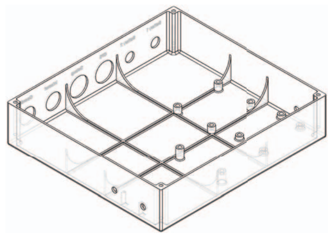
We used Kenwood TH-D72A handheld radios, which include built-in hardware for sending AX.25 frames. While the short information and status messages exchanged by CATAN nodes seem to map well to unnumbered AX.25 data frames, we identified some practical limitations that affected the scalability. First, the data rates supported by AX.25 implementations (i.e. terminal node controllers) are typically limited to 1200 or 9600 bits/sec. At these low-data rates, synchronization of node databases across the network is not practical for more than a small number of nodes and low-rates of data entry. Second, typical hardware implementations do not support flow-control signaling, which limits their utility for broadcast oriented communications over a congested channel, since there is no way of knowing when data will be transmitted.

D. Routing

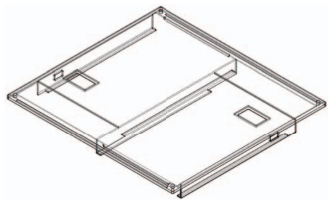
The nodes use a simple flooding protocol over their back-end datalinks to communicate and synchronize data. Each node is assigned a Node ID at startup. Each message contains *Path* and *Visited* fields with a bit set for every destination Node ID. For broadcast messages, all the *Path* bits are set. If a node receives a message that it has not seen before, then it rebroadcasts the message after removing its Node ID from the *Path* field and setting its bit in the *Visited* field. By ensuring that nodes only accept messages that they have not yet seen, and only forward messages with empty visited bits, we can ensure that every node will eventually receive every message. In the case of a disconnected node, we have implemented a re-transmission protocol based on unique message identifiers. Each node periodically broadcasts its global positioning system (GPS) coordinates and the identifier of the most recently sent message. This enables every node to have a global view of the current network state and ensure synchronization.

E. Power and Deployment

The nodes are powered by two 20,000 mAh rechargeable batteries, which allow operation for approximately 18 hours, according to our testing. This should be sufficient for most



(a) Bottom



(b) Top

Fig. 2: CATAN case design

HADR and Public Safety shifts of up to 12 hours and replaceable during a shift change. A solar-cell power source, common HADR technology, could also be easily attached using the external charging port. The entire prototype is packaged in to a custom-designed enclosure (See Figure 2), which has external connectors for antennas; and USB and Ethernet ports for connecting to the Raspberry Pi (for monitoring and gateway operation). These parts are rated to be splash resistant and enhance environmental durability.

The entire prototype node, configured with a Wi-Fi backend, weighs 4.47 lbs. Notably, the batteries are the heaviest components at 510 g (1.12 lbs) each for a combined weight of 1020 g (2.24 lbs). It can be easily carried in a backpack or deployed via tethered balloon or drone. Many vertical take-off and landing drones purchased by U.S. Public Safety organizations have payload capacities of 10+ pounds.

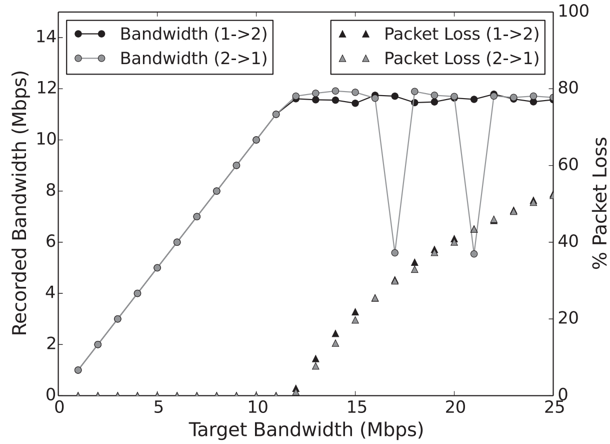
IV. Feasibility Testing

To evaluate network performance and feasibility, we tested our system in a controlled RF-environment and in the field. While an IDP service was prototyped, the emphasis was not on evaluation of use cases. Testing focused on RF performance of the interfaces and evaluation of the underlying mesh protocol.

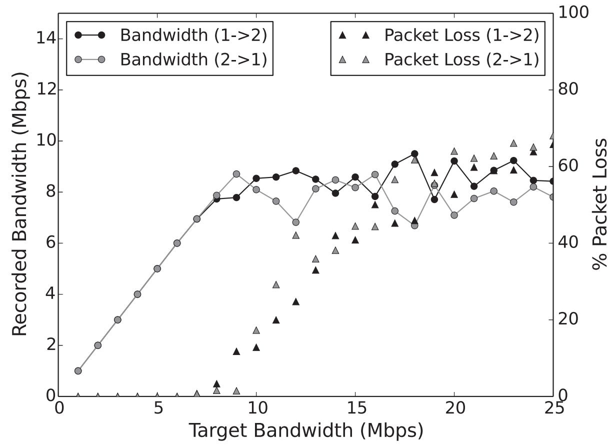
A. Bench Testing

In our experiment, we used two nodes each configured with Ubiquiti WiFi radios as the backend data links. The Wi-Fi radios each have separate transmit and receive SubMiniature version A (SMA) ports. We connected the two nodes by bridging their radios' SMA connectors (*Tx* to *Rx*) with shielded co-axial RF cables and signal attenuators. To prevent RF leakages and contamination, one of the nodes was placed inside a shielded container.

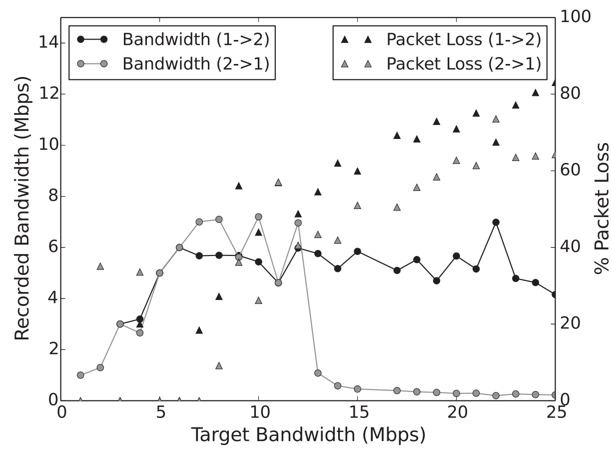
We adjusted our attenuators to create path loss conditions in our cables comparable to real world distances between transmitter and receiver. Each radio operated at 2.4 GHz and output power at 10 dBm at the Tx connector with no antenna attached. We measured the background noise level at -95 dBm. To maintain at least 90% link quality, we found that we needed a receive signal of at least -77 dBm at the Rx connector. This corresponds to a signal-to-noise ratio (SNR) 18 dB and allows for a path loss of approximately 87 dB. We also planned to use the radios with a 9 dBi antenna on both Tx and Rx connectors to obtain an additional 18 dB of gain. At 14 dB, the link quality dropped to approximately 50%. Using the standard free-space path loss (FSPL) equation (1), we computed that SNR levels of



(a) 30 dB SNR (0.5 km)



(b) 18 dB SNR (2 km)



(c) 14 dB SNR (3 km)

Fig. 3: Throughput and packet loss for various signal to noise ratios using our backend mesh network.

30 dB, 18 dB, and 14 dB with this configuration corresponds to distances of approximately 0.5 km, 2 km, and 3 km respectively between transmitter and receiver.

$$FSPL = 20 \cdot log\left(\frac{4\pi d}{\lambda}\right) dB \tag{1}$$

Thus, we adjusted our attenuators so that the two radios had an average SNR of 30 dB, 18 dB, and 14 dB, and we conducted network throughput and packet loss tests for each SNR value. We used iperf, an industry-wide standard network testing tool, to create data streams and measure the throughput of a network. We ran our tests in full-duplex mode, wherein both nodes were sending and receiving simultaneously. For each test, we transmitted data at specified throughput speeds from 1 Mbps to 25 Mbps from both nodes, and we measured the actual throughput achieved and the resulting packet loss. Figure 3 shows our results.

For both SNR 30 dB and 18 dB, we were able to achieve our desired throughput until our backend link saturated at approximately 12 Mbps and 8 Mbps respectively. For SNR 14 dB, performance was worse due to much higher packet loss, but we could still maintain throughput of 1 Mbps from each side with no loss. Due to the small size of our messages, 1 Mbps is sufficient bandwidth for CATAN's backend needs. This is greater than what an NGO's experience in 2015 Nepal.

Note that our bench test did not quantify the potential number of simultaneous users accessing a CATAN node. However, previous research has shown that under normal conditions, over 2000 users can be accessing a public Wi-Fi AP [39].

B. Boston Field Test

We conducted our field test in Boston and Cambridge in January of 2015. Our primary goal was to determine how CATAN would perform in an adverse metropolitan setting after a disaster. We selected an urban environment because it would provide higher ambient RF noise levels and a realistic distribution of RF-impeding buildings and other objects. The observed noise levels from our test can be seen in Figure 4. Our secondary goals were to determine how portable and easy it would be to deploy CATAN nodes at street level, and to determine the extent to which we would need to deploy CATAN nodes in elevated positions (e.g., on buildings, drones, or tethered balloons) to achieve line of sight propagation between nodes. The tallest building in the area was 295 ft high.

For the test, we split into three teams, where each team carried a node in a backpack and walked around parts of MIT campus (and inside its boat house) and on the Harvard Bridge for one hour. During the test, we continuously recorded GPS coordinates, timestamp, SNR, background noise level, and link quality between nodes. As we walked around, we also used mobile phones to add status information to our IDP service to the nodes the same way that actual users would to test our syncing functionality In the test, one of the nodes (Node 2) was set at a stationary point on the side of a river to permit line of sight to the teams on the other side. Figure 5 shows the recorded link quality of the mesh network between two of the nodes for the duration of the test. Note that this figure shows each node's point of view. We find it promising that we were able to achieve up to 100% link quality for distances up to 700 m, and reasonable connectivity up to 1 km.

After returning from the field, we connected a node to the internet via an ethernet connection and successfully synced our IDP service with a test instance of Google Person Finder.

V. System Evaluation

Emergency equipment can be evaluated using the following criteria: portability, durability, standards-based connectivity, ease of use, and availability of an internal power source [40]. Each criterion is rated on a three-factor scale of insufficient, limited, or exceptional. These criteria have been previously used to evaluate Public Safety communication technologies [13], [15].

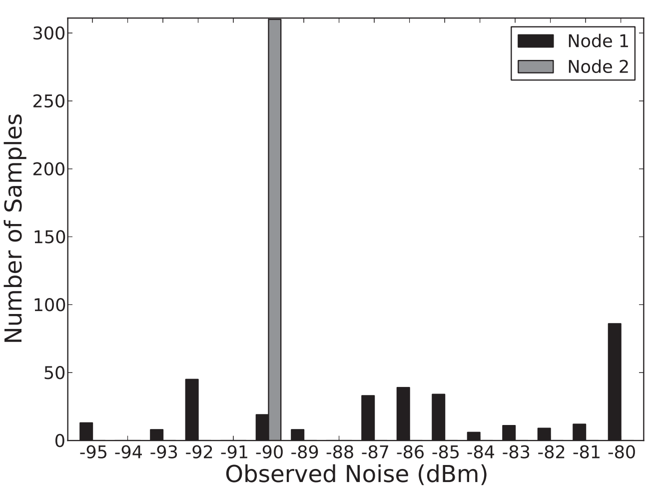


Fig. 4: Observed noise from nodes deployed in field test. (Node 2 was held stationary while node 1 was moving)

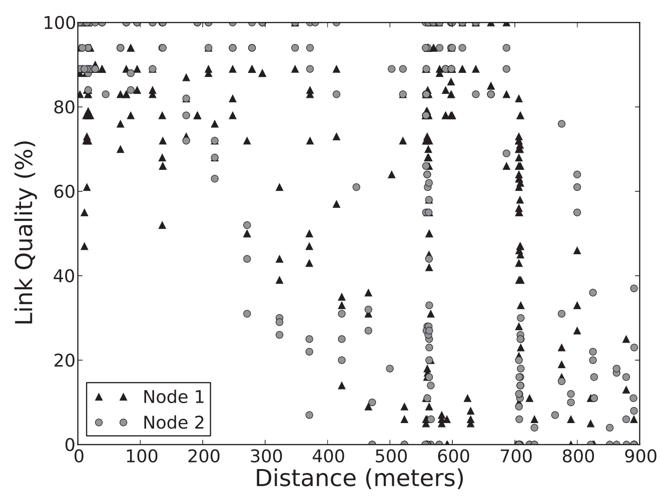


Fig. 5: Relative link quality between nodes 1 and 2 during our field test, as reported by the Ubiquity router.

TABLE III: Prototype Design Evaluation

Criteria	Score	Description
Portability	Exceptional	Small and light enough for international commercial air carry-on baggage and easy man-portable
Durability	Exceptional	Rating meets IP67. It is protected against dust and water
Standards	Exceptional	Technology is an internationally recognized standard for both configuration and end-users
Internal Power	Exceptional	Includes an internal, removable, interchangeable battery source
Ease	Exceptional	System can be configured through a built-in interface requiring no additional software or equipment

A. Hardware and Software

Portability addresses the overall size and weight of the system. Environmental *durability* assesses how well the equipment can withstand typical and extraordinary weather conditions. The durability metrics adhere to those specified by the IEC 60529 [41] international standard. The *standards-based* connectivity criterion addresses the ability to ensure the interoperability of equipment in the field. Similarly, it is important to maintain the ability to quickly repair or replace malfunctioning equipment, which is can be prohibitively expensive with proprietary technology. The *ease of use* criterion evaluates the usefulness of field equipment to someone with minimal training or setup. The *internal power* criterion ensures that the system has an internal, easily-replaced power source, that is independent of the local power infrastructure.

In our assessment, CATAN's design achieves the best score for all criteria (see Table III). Note that a 3D-printed version of our enclosure has limited environmental durability but still meets IP54. However, the enclosure could be built with more durable materials to withstand more harsh environments.

B. Cost and Open Source Evaluation

Table IV lists each of the main components for a CATAN node with a standard 802.11 Wi-Fi front end and and a modified Wi-Fi mesh backend. Note that over a third of the cost is contributed to the batteries, however leveraging FOSS significantly reduces cost. More importantly, each of the components leverage standard interfaces, such as USB, and are common DIY components. This helps ensure that CATAN is flexible and cheap enough to be included in a "disaster kit." Similarly, CATAN can be rapidly assembled by HADR groups and provide a leave-behind capability at the affected region.

VI. Future Work

While CATAN fulfills our initial design goals, we have since identified some potential directions for future development. For example, photographs have been shown to be invaluable for data sharing applications. We hope to add more photograph functionality to our system (e.g., Snapshot [43], image recognition), while remaining cognizant of both our computational and bandwidth constraints. Similarly, our web-based interface only offers limited access to the user (i.e. users only "pull" information). We are advocating for an application store that will enable users to download native applications, capable of providing a more seamless and responsive experience (e.g., "push" notifications). Finally, we hope to continue maturing our network protocols to simply the mesh network configuration and minimize the interaction required when bootstrapping a new node.

TABLE IV: Baseline CATAN Node Cost

Component	Name	Quantity	Cost
Batteries	Anker AK-79AN7906-BA	2	$160
RF Link	Ubiquiti Rocket M2	1	$80
Computer	Raspberry Pi B+	1	$45
802.11 Wi-Fi radio	ThinkPenguin TPE-N150USBL	1	$40
GPS Receiver	GlobalSat BU-353	1	$40
Antennas	MonoPrice +9dBi	2	$20
Operating system	Raspbian Linux	1	$0
Total	**Node**	**1**	**$385**

A

VII. Conclusion

While many internet services exist to track and identify missing or injured persons, disasters often impair the communication infrastructure required to accesses these services, which hinders the ability to conduct an effective HADR response. CATAN, a rapidly-deployable communication infrastructure, is able to re-enable these communications and collect vital information from both survivors and responders. By leveraging popular DIY FOSS, CATAN is able to provide a flexible development and deployment environment, while maintaining a low system cost. CATAN was tested in both a bench and urban environment to ensure that the system was able to meet current HADR data requirements. The CATAN software, including the enclosure models, are freely available on Github (https://github.com/mit-ll) under a BSD license, enabling others to expand the technology or build their own CATAN nodes.

Acknowledgment

We would like to thank our colleagues, Charles Cimet and Masato Kocberber, for all of their work on the project; Mischa Shattuck, Franz Busse, Paul Breimyer, and Amna Greaves for their invaluable insights and guidance; and Bernadette Johnson for making the entire project possible. We also like to thank Stephen Hunt and Team Rubicon for their insights.

References

[1] J. Western and J. S. Goldstein, "Humanitarian intervention comes of age-lessons from somalia to libya," *Foreign Affairs*, vol. 90, p. 48, November 2011.

[2] P. Meier, *Digital Humanitarians: How Big Data Is Changing the Face of Humanitarian Response*. Crc Press, 2014.

[3] M. Zook, M. Graham, T. Shelton, and S. Gorman, "Volunteered geographic information and crowdsourcing disaster relief: a case study of the haitian earthquake," *World Medical & Health Policy*, vol. 2, no. 2, pp. 7–33, July 2010.

[4] A. L. Hughes, L. A. A. St. Denis, L. Palen, and K. M. Anderson, "Online public communications by police & fire services during the 2012 hurricane sandy," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '14. New York, NY, USA: ACM, 2014, pp. 1505–1514. [Online]. Available: http://doi.acm.org/10.1145/2556288.2557227

[5] A.-M. Corley, "Why Haiti's Cellphone Networks Failed," February 2010, Accessed: 05/05/2015. [Online]. Available: http://spectrum.ieee.org/telecom/wireless/why-haitis-cellphone-networks-failed/1

[6] M. Farrell, "Cellphone networks overwhelmed in blast aftermath," The Boston Globe, April 2013, Accessed: 05/29/2015. [Online]. Available: http://b.globe.com/17FscMg

[7] Public Safety Communications Research, "Location-Based Services R&D Roadmap Report ," National Institute of Standards and Technology, NIST Technical Note 1883, May 2015. [Online]. Available: http://dx.doi.org/10.6028/NIST.TN.1883

[8] I. Rubin, A. Behzad, H.-J. Ju, R. Zhang, X. Huang, Y. Liu, and R. Khalaf, "Ad hoc wireless networks with mobile backbones," in *15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, 2004. PIMRC 2004*, vol. 1, 2004, pp. 566–573 Vol.1.

[9] R. Winchester, "Design and operational considerations of an aerostat communications system for emergency response," in *8th Annual (IT-ERA) Conference On Telecommunications & Informaiton Technology*, Nashville, TN, Apr. 2010.

[10] T. Wypych, R. Angelo, and F. Kuester, "AirGSM: an unmanned, flying GSM cellular base station for flexible field communications," in *2012 IEEE Aerospace Conference*, 2012, pp. 1–9.

[11] A. Valcarce, T. Rasheed, K. Gomez, S. Kandeepan, L. Reynaud, R. Hermenier, A. Munari, M. Mohorcic, M. Smolnikar, and I. Bucaille, "Airborne base stations for emergency and temporary events," in *5th International Conference on Personal Satellite Services*, Toulouse, France, Jun. 2013. [Online]. Available: http://arxiv.org/abs/1307.3158

[12] A. Weinert, P. Breimyer, S. Devore, J. Miller, G. Brulo, R. Teal, D. Zhang, A. Kummer, and S. Bilen, "Providing communication capabilities during disaster response: Airborne remote communication (ARC) platform," in *2012 IEEE Conference on Technologies for Homeland Security (HST)*, 2012, pp. 395–400.

[13] A. Weinert, P. Erickson, H. Reis, P. Breimyer, T. Hackett, M. Samperi, J. Huff, C. Parra, E. Stoekl, P. Zundritsch, R. Morris, I. Iakimenko, E. Petschauer, and S. Bilen, "Enabling communications in disadvantage environments: An airborne remote communication (ARC) platform," in *2013 IEEE International Conference on Technologies for Homeland Security (HST)*, Nov. 2013, pp. 797–803.

[14] G. Kovcs and K. M. Spens, "Humanitarian logistics in disaster relief operations," *International Journal of Physical Distribution & Logistics Management*, vol. 37, no. 2, pp. 99–114, 2007. [Online]. Available: http://dx.doi.org/10.1108/09600030710734820

[15] K. Chang, M. Kozar, C. Rose, A. Weinert, P. Breimyer, R. Di Ciaccio, T. Roe, C. Timmerman, and S. M.A, "A review of satellite communications and complementary approaches to support distributed diaster relief," MIT Lincoln Laboratory, Lexington, MA, Technical Report, Apr. 2013.

[16] B. S. Manoj and A. H. Baker, "Communication challenges in emergency response," *Communications of the ACM*, vol. 50, no. 3, pp. 51–53, 2007.

[17] R. Lee, J. Manner, J. Kim, B. Hurley, P. Amodio, and K. Anderson, "White paper: The role of deployable aerial communications architecture in emergency communications and recommended next steps," Federal Communications Commission, Washington, DC, White Paper DOC-309742A1, September 2011.

[18] M. Rak and P. Pechac, "UHF propagation in caves and subterranean galleries," *IEEE Transactions on Antennas and Propagation*, vol. 55, no. 4, pp. 1134–1138, 2007.

[19] P. Svensson, "Hurricane sandy knocked out 25 percent of cell towers in its path," October 2012. [Online]. Available: http://read.bi/Rr7zJa

[20] K. Jun, E. Bellman, and J. Hookway, "Scant Cellphone Service Brings Out Old-School Phones in Typhoon-Hit Samar," November 2013, Accessed: 05/05/2015. [Online]. Available: http://on.wsj.com/1zEoRd0

[21] *NTA-MIS-94*, ser. MIS Reports, vol. 122, no. 1, Nepal Telecommunications Authority, March 2015.

[22] Pew Research Center, "Mobile Technology Fact Sheet," May 2015, Accessed: 05/05/2015. [Online]. Available: http://www.pewinternet.org/fact-sheets/mobile-technology-fact-sheet/

[23] P. Meier and R. Munro, "The unprecedented role of sms in disaster response: Learning from haiti," *SAIS Review of International Affairs*, vol. 30, no. 2, pp. 91–103, 2010.

[24] M. Geuss, "After Nepal earthquake, people turn to ham radio," April 2015, Accessed: 05/05/2015. [Online]. Available: http://ars.to/1J6KK9z

[25] J. Scanlon, T. McMahon, and C. Van Haastert, "Handling mass death by integrating the management of disasters and pandemics: Lessons from the indian ocean tsunami, the spanish flu and other incidents," *Journal of Contingencies and Crisis Management*, vol. 15, no. 2, pp. 80–94, 2007.

[26] F. Luqman, F.-T. Sun, H.-T. Cheng, S. Buthpitiya, and M. Griss, "Prioritizing data in emergency response based on context, message content and role," in *Proceedings of the 1st International Conference on Wireless Technologies for Humanitarian Relief*. ACM, 2011, pp. 63–69.

[27] Raffi Krikorian, "Twitter by the numbers," Youtube, September 2010. [Online]. Available: http://youtu.be/TdY0jU697lY

[28] "Global estimates 2011: People displaced by natural hazard-induced disasters," June 2012. [Online]. Available: http://www.unhcr.org/50f95fcb9.html

[29] Google.org, "Google Person Finder," May 2015, Accessed: 05/05/2015. [Online]. Available: https://google.org/personfinder/global/home.htm

[30] "Restoring Family Links," May 2015, Accessed: 05/05/2015. [Online]. Available: http://familylinks.icrc.org/en/Pages/home.aspx

[31] Facebook.com, "Safety Check," Accessed: 05/05/2015. [Online]. Available: https://www.facebook.com/about/safetycheck/

[32] H. Tabuchi, "Quick Action Helps Google Win Friends in Japan," *The New York Times*, Jul. 2011. [Online]. Available: http://nyti.ms/1EdmuOM

[33] M. Zuckerberg, Facebook Post, Apr. 2015, Accessed: 05/05/2015. [Online]. Available: https://www.facebook.com/zuck/posts/10102060884238261:0

[34] K.-P. Yee, "PFIF," May 2015, Accessed: 05/05/2015. [Online]. Available: http://zesty.ca/pfif

[35] United States and United States Coast Guard, "U. S. COAST GUARD ADDENDUM TO THE UNITED STATES NATIONAL SEARCH AND RESCUE SUPPLEMENT (NSS) to the international aeronautical and maritime search and rescue manual (IAMSAR)," U.S Department of Homeland Security, Washington, DC, Addendum COMDTINST M16130.2F, Jan. 2013.

[36] J. G. Tanenbaum, A. M. Williams, A. Desjardins, and K. Tanenbaum, "Democratizing technology: pleasure, utility and expressiveness in diy and maker practice," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 2013, pp. 2603–2612.

[37] "Google Maps Javascript API v3," May 2015, Accessed: 05/05/2015. [Online]. Available: https://developers.google.com/maps/documentation/javascript/

[38] W. A. Beech, D. E. Nielsen, and J. Taylor, "Ax. 25 link access protocol for amateur packet radio," *Tucson Amateur Packet Radio Corporation*, pp. 1–133, 1998.

[39] M. Afanasyev, T. Chen, G. M. Voelker, and A. C. Snoeren, "Analysis of a mixed-use urban wifi network: When metropolitan becomes neapolitan," in *Proceedings of the 8th ACM SIGCOMM Conference on Internet Measurement*, ser. IMC '08. New York, NY, USA: ACM, 2008, pp. 85–98.

[40] J. G. Gabriel, "Right technology, right now: An evaluation methodology for rapidly deployable information and communications technologies in humanitarian Assistance/Disaster relief," Master's Thesis, Naval Postgraduate School, Monterey, CA, Mar. 2012.

[41] National Electrical Manufacturers Association, "ANSI/IEC 60529-2004," National Electrical Manufacturers Association, Rosslyn, Virginia, Approved American National Standard, Nov. 2004.

[42] "dixprs," May 2015, Accessed: 05/05/2015. [Online]. Available: https://sites.google.com/site/dixprs/

[43] "ICRC in South Sudan: Facts and Figures," February 2015, Accessed: 05/05/2015. [Online]. Available: http://familylinks.icrc.org/en/Pages/NewsAndResources/News.aspx

[44] J. Mpala and G. van Stam, "Open bts, a gsm experiment in rural zambia," in *e-Infrastructure and e-Services for Developing Countries*, ser. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, K. Jonas, I. Rai, and M. Tchuente, Eds. Springer Berlin Heidelberg, 2013, vol. 119, pp. 65–73.