EmergenCell Design and Technical Documents

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1 Introduction

Our project for the Mozilla WINS challenge, EmergenCell, is a self-contained, open source, backpack-sized LTE "network in a box" designed to be incredibly simple and straightforward for a non-expert to deploy. EmergenCell comes pre-packaged with many local web-based services that support users' basic needs in the wake of a natural disaster, even without Internet connectivity. In this document, we provide a system overview, details of the individual system components, and technical specs where possible.

2 Technical Overview

2.1 Problem Context and Deployment Assumptions

A key step in designing or building any network is to explicitly identify the constraints and assumptions fueling the network design. Though natural disasters are obvously hard to predict, and vary tremendously in terms of the damage caused and challenges presented, we wanted to (1) explicitly identify our assumptions and reliances and (2) support as wide a range of disasters as possible (by assuming or requiring as little as possible). The following list enumerates our assumptions about the disaster space and population itself:

- The standard telecom infrastructure (e.g. cell towers and/or broadband connections) in the area is rendered inoperable.
- The majority of people in the affected area have direct or indirect access to an LTE-capable phone.
- The population in the affected area does *not* have access to reliable power.
- The population in the affected area has not prepared for the disaster in any form. These preparations could include, but are not limited to, charging their devices, purchasing an emergency response device, or obtaining a SIM card.

These assumptions, particularly the last one, led us to a deployment vision that our EmergenCell units are likely to be owned, managed, and deployed *after* a disaster by emergency response organizations such as the Red Cross or FEMA. Working off of this vision, the EmergenCell team met with representatives from various emergency response organizations to validate our assumptions and collect information regarding the network and infrastructural conditions faced by organizations in these contexts. From these meetings, we learned that we could assume and rely upon the following network characteristics:

- Reliable electrical power (either grid or generated) exists in select central locations, such as a makeshift response headquarters.
- Some form of Internet backhaul (either wired, wireless, or satellite) also exists in these same central locations; this backhaul can be heavily constrained.
- The organizations we met with uniformly expressed that they felt that backhaul connectivity was barely sufficient for their operations, and explicitly expressed a lack of interest in sharing the backhaul with the broader population.

2.2 System Architecture

Traditional LTE networks are largely centralized, and consist of individual cell towers (known as eNodeBs) connected over an Internet (or Intranet) connection to the network core, called the EPC. The EPC powers and controls the towers, and handles logistics such as authentication, mobility, network routing and interconnect. Figure 1 illustrates a traditional LTE network, and underscores the fundamental challenge of providing LTE connectivity in disconnected areas: without a connection to the Internet, the cell towers are unable to reach the EPC, and as a result cannot perform any network operations whatsoever.

In contrast to this architecture, an EmergenCell network is a small-scale, local, and self-contained LTE network, consisting of a single eNodeB physically

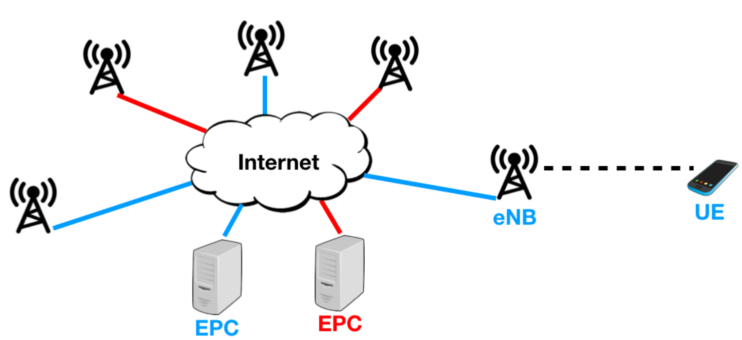

Figure 1: Traditional LTE Architecture

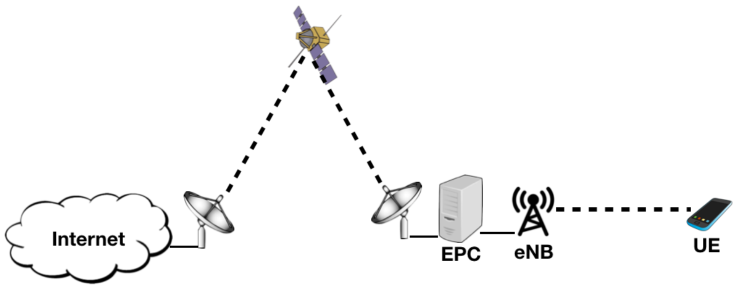

Figure 2: EmergenCell Architecture

colocated with the EPC. This physical colocation means that the EmergenCell network is able to support all the necessary network functions listed above regardless of the presence of an Internet backhaul. Figure 2 illustrates an EmergenCell connected to the Internet via a satellite link.

2.3 Why LTE

Despite the popularity of unlicensed spectrum access technologies such as WiFi, and despite the excitement around new and novel spectrum proposals such as TVWS, we chose LTE as the core access technology over which to build our EmergenCell system. We chose LTE for many reasons, including user adoption, performance, and an all-IP base.

User Adoption: LTE support is rapidly increasing throughout the cellular handset ecosystem. In the United States, approximately 74% of cellular connections were already LTE-based as of Q4 2017 [1]. This high threshold of support ensures that an EmergenCell unit will be able to reach a high fraction of users in an area, on their existing hardware, *without* requiring users to obtain new devices. Note that the percentage of cellular connections is not authoritative, and is best understood a *floor* to the number of handsets in the area that are capable of supporting LTE. For example, our 2017 study [2] of a 2G rural Indonesian cellular network found LTE support in approximately 30% of connected handsets.

Range: The LTE protocol stack can provide fast connection speeds (up to 150 Mbps advertised) at a radius of up to 30km for LTE macrocells. This range is exceedingly impressive when compared to WiFi-based approaches (average radius of 50m). Especially when considered in the disaster context, rife with unknown obstacles and damaged infrastructure, this large range is vital, in no small part because it enables a single EmergenCell unit, provisioned at a first responders' HQ, to quickly and easily support and contact users across a wide geographic area.

IP Substrate: In contrast to prior generations of cellular networks, the network primitive in LTE is IP packets. This convergence to an all-IP base, as opposed to virtual or physical network circuits, makes it incredibly easy to implement a wide variety of network services as websites, and provides us with many other IP-based tools (e.g. DNS redirection, traffic filtering, etc.).

3 Technical Details

3.1 Roaming and Emergency Attach:

In our initial WINS submission, our team proposed to explore the possibilities of leveraging the LTE Emergency Attach Procedure, which is designed primarily for routing voice calls to emergency numbers, to "tunnel" IP packets to the base station. This solution would have bypassed the authentication inherent to the LTE protocol, and therefore enabled us to connect to any and all phones in the area, regardless of carrier, and without requiring any backhaul connectivity whatsoever. While we have not completely ruled out this solution for future work, the following discoveries have led us to alter our design:

- VoLTE adoption in carrier networks still lags far behind LTE adoption, and the presence of VoLTE support (or lack thereof) significantly alters the emergency attach procedure.
- We have confirmed with multiple emergency response organizations that their mobile headquarters have Internet backhaul connectivity, typically powered by satellite.
- We have learned that the Public Safety Broadband Network (PSBN) has a single Public Land Mobile Network (PLMN) ID, and that the PSBN *already* has roaming agreements with all US carriers for purposes of extending range.
- We have confirmed that in roaming contexts, the home network handles billing by receiving and processes billing events (i.e. PCRF messages) sent from the visited network.

When combined with our earlier deployment assumptions (specifically that EmergenCell units will be operated by emergency responders at a headquarters), these discoveries led us to replace our earlier design with a slightly different architecture. In our new design, the EmergenCell will require a limited Internet connection at the responders headquarters, and will use this connection *only* to establish a Diameter S6A connection with other telecom carriers to perform roaming network authentication as handsets attach to the network. The primary drawback of this approach is that it does in fact require limited Internet backhaul connectivity for purposes of roaming authentication. However, this disadvantage is trivial in our target deployment context, and must be weighed against the substantial benefits, which include (1) LTE-grade authentication and security; (2) a default, well-understood and well-supported roaming architecture (as opposed to a may-or-may-not-work emergency attach procedure); and (3) this design avoids a reliance on VoLTE/IMS integration and support.

With the exception of the handset attach procedure, the EmergenCell does not perform any other signaling or message exchange with the carrier's network, and will not (by default) bridge the handset's traffic to the Internet. By instructing the handsets to use EmergenCell's onboard S-GW, EmergenCell will then ensure that the handset's GTP traffic is terminated locally and not tunneled over the Internet connection to the carrier's network. With this connection, EmergenCell provides users with the local webservices and content described below completely free of charge, by simply not sending PCRF billing event messages to the carrier networks. Finally, by connecting to EmergenCell as a roamed network, visiting handsets will seek to return home as soon as possible. This is a tremendous boon to our system, because it means that as telecom carriers in the area restore coverage, phones will automatically switch back to their carrier's network, thereby ensuring that the EmergenCell network is only used by handsets that still lack coverage.

3.2 Bridging Internet Access

As mentioned above, EmergenCell requires sufficient Internet connectivity to perform a roaming authentication exchange (two datagrams of approximately 500 bytes each) when a handset joins the network. We explicitly do *not* assume that there exists sufficient bandwidth for EmergenCell users to use general Internet features such as web browsing, nor do we assume that the network administrators wish to share this bandwidth with the general population. However, if such bandwidth is in fact available, and if the operator wishes to share it, then the finished EmergenCell product will provide a way for administrators to turn on or off upstream Internet connectivity, along with basic traffic-shaping tools. These tools could block certain high-bandwidth services such as YouTube, throttle or rate-limit individual users, or simply prioritize low-bandwidth and high-value services such as WhatsApp, Messenger, and email.[1] Please note that all of these use-cases and features are trivial to support with basic tools such as `ipfw` and `qdisc`, because traffic bridged from the LTE network to the Internet is simply NATed and routed through the EmergenCell kernel as IP traffic.

4 Bands and Spectrum

There exist over fifty different LTE bands [3], and many different factors go into selecting the best band for a given situation. These factors include handset support, conflict with existing carriers, distance and range, and laws/regulations. Fortunately, everything related to choice of band is contained entirely at the eNodeB: this modularity and our integration with unmodified eNodeB hardware means that changing bands is a very easy and straightforward process of simply

[1] In our Indonesian network, we have had explicit community requests for traffic prioritization of these low-bandwith OTT services, and are currently building out a system to accomplish this.

choosing a different hardware platform. As such, we do not claim that EmergenCell uses any one specific band - rather, in this section we discuss some of the different considerations in selecting a specific band for a specific use.

Handset Support: Most LTE-capable phones support anywhere from five to ten different LTE bands, and these specific bands vary based on the hardware manufacturer and intended market. For example, the European/African version of the Motorola Moto C supports bands 1, 3, 5, 7, 8, and 20, whereas the Latin American version supports bands 2, 3, 4, 7, and 28. The set of bands supported in handsets tend to be influenced primarily by the bands used by the major telecom providers in a specific country or region, and as a result, political boundaries play a surprisingly strong role in selecting the best band for a given disaster.

Carrier Conflict: If a major carrier in the region operates on a specific band, the handsets sold in this region are likely to support that band. However, major carriers also present a reason *not* to use this band, as well - the goal of EmergenCell is to provide emergency connectivity to disconnected users, not to interfere with existing telecom operations. It follows that during the band selection process, steps should be taken (either via scanning the area or requesting current coverage maps from the carriers present in the area) to ensure that EmergenCell does not interfer with other active cellular carriers in the region.

Non-Cellular Uses: Interestingly, not every LTE band is provisioned for LTE in all countries. As an example, Band 8 is used for commercial LTE in Indonesia, but reserved for other uses in the United States. This fragmentation presents both challenges and opportunities towards selecting the correct band for a specific context: while extra care must be taken to avoid conflicts with non-cellular operators, certain bands may be supported by local handsets and guaranteed to not be operated on.

Distance and Range: Depending on the specific frequency employed, different bands are affected differently by a wide range of environmental factors such as water vapor, trees, hills, buildings, and more. As a general rule of thumb, lower-frequency bands (e.g. the 850MHz Band 5, or the 900MHz Band8) have much better range and penetration than higher-frequency bands (e.g. the 2.6GHz Band 7). It follows that having accounted for the preceding three factors, we recommend selecting the lowest-frequency band with high handset support - in practice, this is likely to be Band 5, 8, 20, or 28.

Access Rights: Obtaining the legal rights to operate on a specific band is typically a challenging, expensive, and slow process - however, the disaster relief context offers unique opportunities to move quickly, and our goal of partnering with response organizations affords us greater leeway towards influencing policy. For example, the National Guard's position under the Department of Defense, and FEMA's position under the Department of Homeland Security, mean that either organization has the top priority to use whatever frequency it desires, at any time, under FCC Part 15. As another example, the Red Cross is also specifically exempt from spectrum regulation under the Geneva convention.

5 Locally Hosted Services

Given that EmergenCell does not necessarily provide Internet access to its users, it comes pre-loaded with locally hosted, fully offline web apps to support basic user needs. When users join the EmergenCell network, they will receive an SMS instructing them to go to `http://home.emergency` to access the local services. This website is a simple landing page, shown in Figure 3, that links to other locally-hosted EmergenCell services. Note that certain buttons are greyed out not for lack of functionality, but simply to show that we are able to dynamically enable or disable individual services.

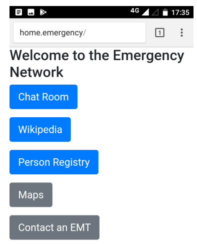

Figure 3: EmergenCell Homepage

5.1 Service 1: Maps

The number one rule in emergency response is to stay safe and not add to the emergency. In the wake of a natural disaster, users first and top priority is always to stay alive and safe - and this means locating food, water, shelter, medical aid, and more. EmergenCell helps users meet these fundamental needs with a simple and interactive mapping application hosted at `http://maps.emergency`. With this application, users can see their location on the map, add their own notes, and mark (with a timestamp) the locations of food, water, aid, and shelter in a crowdsourced manner. Figure 4 provides a screenshot of the mapping service in action, with user-populated icons indicating food and water to the north, and a fire on the highway to the south.

We built this offline mapping service by forking the OpenStreetMaps code from their github account. While intended to be plug-and-play, our team spent significant effort setting up the application in a virtual machine and connecting it to a similarly locally hosted maptile server (run in a Docker container). With both servers running locally, we then downloaded the correct set of maptiles from the OpenMaptTiles project and prepopulated the server with them, to ensure that no Internet connectivity is needed to support this effort.

5.2 Service 2: Person Registry

Once users' immediate needs are taken care of, their thoughts almost immediately turn to their loved ones. To support this need, we designed a simple registration webapp hosted at `http://registry.emergency` that allows users to perform three basic functions: register (or update) their own information, register on behalf of someone else, or search for someone by name or phone number. This registration app, shown in Figure 5, allows users to input their

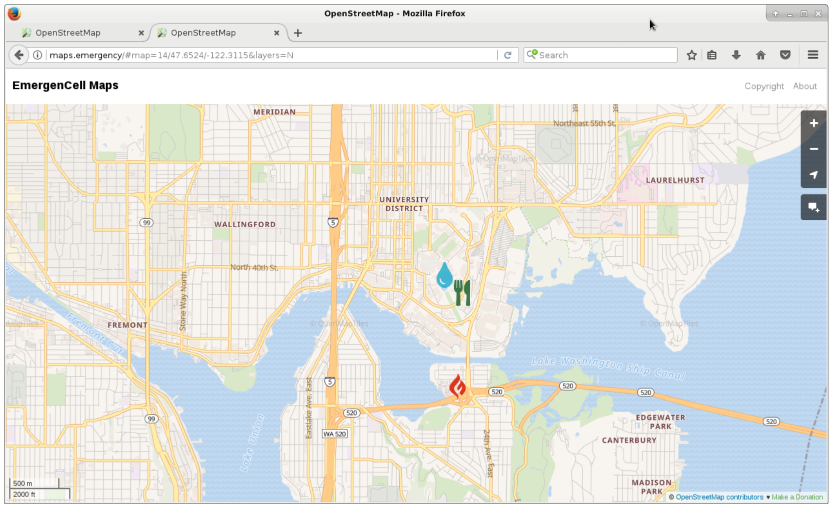

Figure 4: Locally Hosted Mapping Server

name, phone number, location, status, and anything else they might wish to share about themselves.

We specifically chose to provide the user with text-fieldsfor manual entry in lieu of more automated solutions (i.e. scraping the phone number from the SIM or using the phone's location services to pull GPS coordinates) for two main reasons. First, it significantly reduces the overhead on user devices, both in terms of network traffic as well as power consumption. Second, and more importantly, it embraces a *descriptive over prescriptive* design philosophy that gives users much more flexibility to describe situations that are likely unorthodox or improvised. For example, "north end of the Red Cross camp, under the big palm tree" provides much more descriptive and helpful context than GPS coordinates, whereas "staying in the Smith's backyard" preserves privacy by conveying location information only to those with the relevant social contextual information.

5.3 Service 3: RocketChat

Building on the above themes of designing for flexibility in order to support unorthodox and improvised situations, we chose to host a RocketChat server at `http://chat.emergency`, shown in Figure 6. RocketChat is an open-source chat engine, similar to Slack in that it supports a general chatroom, direct messages, and allows users to make different channels named around whatever topic they choose. We do not yet have a clear vision or model of how users will interact with this chatroom, and imagine that the uses will be incredibly specific and localized to the community and the disaster, but we take our inspiration from studies that have found Slack to be an incredibly diverse and flexible tool for

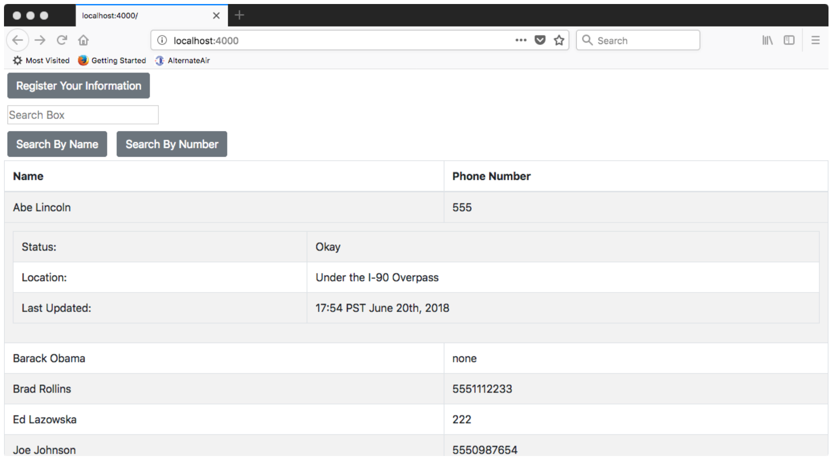

Figure 5: Person Registry

community management, organization, and information dissemination. Some example channel uses could include missing persons, lost and found, availability of (and barter for) resources, announcements, warnings, and general queries about the current situation.

5.4 Service 4: Media Server

While streaming media is clearly not necessary for survival, available media is widely considered to be a vital tool for increasing morale in distressed situations ranging from hospital work to military operations. Applied to our scenario, we decided to host a local streaming media server not for immediate recovery tasks (i.e. locating people in distress) but to improve morale and ease livability for users during the slow, post-disaster recovery process as people return home from camps. For this media server, we chose to use UMS (the Universal Media Server, an open-source project forked from the PS3 Media Server) for its open-source license, ease of setup, transcoding support, fully offline operation, support for mobile devices, and ease of operation.

With UMS, the operator simply places videos (or music) in a folder, and the UMS server automatically detects it, transcodes it, and advertises it for Web streaming. Note that while we do not explicitly endorse sharing pirated content, we do anticipate that given the extenuating circumstances and limited usefulness of the emergency network, media creators (such as Netflix) would be interested in donating or licensing media content.

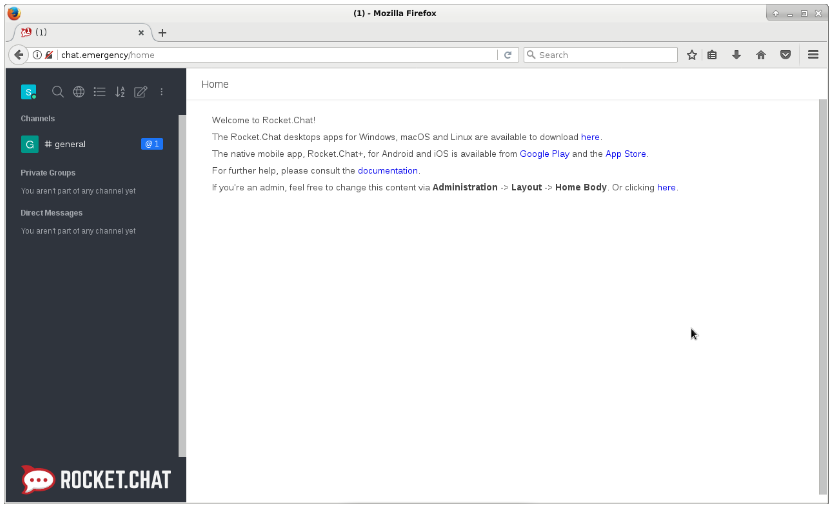

Figure 6: RocketChat Homepage

6 Performance Metrics

We built our testbed EmergenCell out of a BaiCells commercial-grade eNodeB connected to a Zotac ZBox. The eNodeB handles the LTE Rado Access Network (RAN) and the ZBox hosts the LTE core logic as well as the offline webservices. While building our prototype, we applied for and were granted an FCC experimental license, which allowed us to operate the cellular network within our basement's anechoic chamber, as long as we induced significant artificial signal attenuation and ensured that the signal did not propagate beyond the chamber.

Speed: Our commercial eNodeB advertises rates of up to 150 Mbps down/50 Mbps up under ideal conditions. In our lab experiments, we consistently saw Internet SpeedTest rates (note that this test measures TCP goodput over both fronthaul and backhaul) of 50 Mbps down/20 Mbps up. However, these metrics were collected (1) with relatively cheap, low-performing handsets; (2) using a 10Mhz channel instead of the ideal 20Mhz; and (3) under significant signal attenuation, which we artificially induced for FCC compliance purposes.

Users: According to BaiCells, the hardware that powers our LTE base station can support 255 simultaneous users. We have not yet verified this metric in our lab, due primarily to the high cost of LTE handsets. Our lab currently possesses three LTE-capable handsets, and was able to confirm that our EmergenCell prototype can connect all three devices simultaneously. Basic system performance benchmarks on the ZBox (i.e. `top` and `free`) showed us that the core overhead of adding additional devices to the network appeared minimal, and that running entire system taxed the ZBox at about 50% of capacity.

Range: Though current LTE macrocells can provide a coverage radius of up to 30km, there are a large range of factors, both device-oriented and environmental, that affect the useful range of an LTE cell. Though the restrictive terms of our current FCC license do not permit us to perform range tests to explore range metrics, we estimate that an EmergenCell unit with strong antennas and proper configuration should be able to provide kilometers of range as a conservative assumption. Fortunately, the EmergenCell shares a hardware base with our community LTE project CoLTE, which is slated for a late July network deployment in Indonesia. During this deployment, mentioned below, we plan to collect and verify these performance metrics.

Power: Initial evaluations on our EmergenCell unit have found that at minimum viable operation, our system (both eNodeB and EPC) requires 65 Watts; we have not yet explored how this is altered by longer range and/or additional handsets. However, it is also worth stressing that the power consumption of an EmergenCell is remarkably asymmetrical by design. This asymmetry lets us place a strong focus on conserving the power draw at *clients* that may or may not have power, even if this creates an increased draw at the server, which we assume to be centralized and located nearby a reliable power source. Note that this approach of prioritizing the conservation of client power can be seen not just in the underlying LTE attach architecture, but also in the architecture of our webservices, which employ RESTful architectures and minimize Javascript whenever possible for the express purpose of minimizing client-side computation. Finally, though we acknowledge that estimated battery-life metrics are famously anecdotal, unreliable, degrade over time, and are affected by a wide range of other factors (ranging from the number of installed apps to ambient temperature), initial tests on our lab handsets (a new Motorola Moto C Plus with a 2350 mAh battery) that simply attached and camped on the network lasted multiple days between charges.

Size and Weight: EmergenCell uses two pieces of commodity off-the-shelf hardware: a Zotac ZBox, which is roughly the size of a hardcover book, and a BaiCells eNodeB, which is roughly the size of a briefcase. Figure 7 provides a picture of a team member holding the Baicells eNodeB, for visual scale and comparison. In total, the system is easily transportable by a single person, and weighs approximately twenty pounds.

Cost: Cost per unit was a predominant factor throughout the process of building our system and selecting a hardware platform. As such, our EPC is a $150 Zotac Zbox, and our eNodeB is a BaiCells commercial product that costs approximately $2200, for an out-the-door total of ~$2500, including antennas and mounting hardware.

CoLTE and Performance Evaluation: In our discussion of performance metrics, it is important to note that we are using the exact same hardware and core software stack in our closely related Community LTE Project (`http://communitylte.wordpress.com`), which is a self-contained LTE network, bridged to the Internet and designed for community Internet access in remote/rural areas. We have successfully obtained a full LTE license in Indonesia, and our first live CoLTE network deployment is scheduled for July. During this deployment,

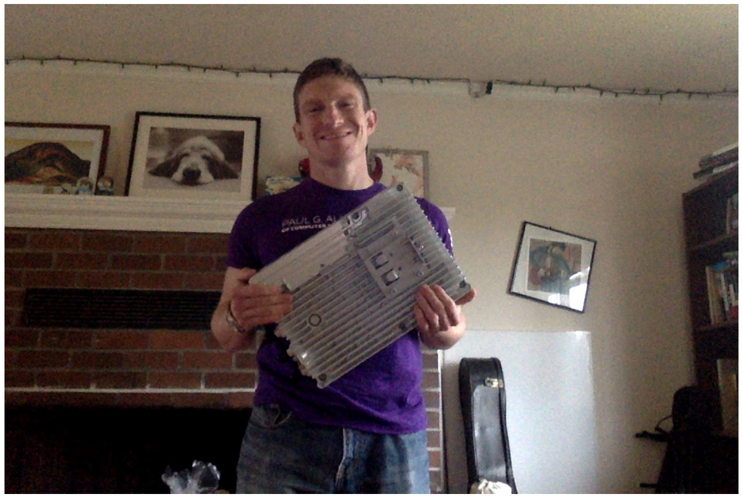

Figure 7: BaiCells eNodeB

we will be collecting and verifying all of the metrics claimed above, and plan to have concrete numbers, observed with real users in in the real world on our production-ready enviroment, in time for the August 14 Demo Day.

Interchangeable eNodeBs: Equally notable is the fact that almost all the aforementioned specs and limitations (speed, simultaneous users, and range) are characteristics and limitations of the eNodeB hardware platform itself. This is incredibly important to stress, because the S1AP and GTPU protocols, by which the eNodeB talks to the EPC, are very well standardized. This standardization means that one eNodeB can easily be replaced with another, and to this point we've currently verified our system with three different eNodeBs. As a result, the aforementioned performance metrics can be thought of not as fundamental to the system, but as metrics bound to cost, in that if any of the metrics are problematic or unsatisfactory in the field, a more expensive eNodeB is certain to bring better performance.

7 Project Status and Future Work

Our current EmergenCell prototype is largely complete. All tentpole features are finished, we have forked our initial release (v0.9), and aside from responsive optimizations of some of our web services, our remaining tasks lie solely in the realms of verification, initial user-testing across a wide range of devices, and collection of real-world performance metrics. Our plans for completing all three of these tasks center around our aforementioned upcoming community LTE network deployment in July. Accounting for schedule-slip or unforeseen challenges during the transition to a live environment, we hope to have an initial released product by September, and to this point we have already started the process of outreaching to disaster relief organizations.

Past the initial technical release, in addition to ongoing technical maintenance, we expect our future work to be largely organizational and logistical across several different fronts. On the disaster relief side, this work will include (1) cultivating a relationship with one or more specific relief organizations, (2) discovering and implementing any specific features, requirements, or restrictions the organization may have, and (3) learning and building to the exact details of the roaming agreement(s) and how to interconnect with the corresponding carriers of an area. With respect to the developer community, we are already strong contributors to the OSS projects that EmergenCell is built on (i.e. OAI, ntop, OSM, and UMS) and have fixed multiple bugs in each project. In these communities, we want to cultivate more of an organizational identity and awareness of the project, with a longer-term goal of building a technical platform that enables any developer to package an offline webapp that could be useful in the relief space and subsequently provide it to EmergenCell users. Finally, additional feature-adds include a system to divide users based on whether they are relief workers or ordinary users, building a set of more specialized tools to specifically aid relief workers, and adding support for non-LTE and feature phones, via text messaging or other interfaces.

References

[1] Lte most widely used cellular technology worldwide at end of 2017. `https://globenewswire.com/news-release/2018/03/22/1444749/0/en/LTE-Most-Widely-Used-Cellular-Technology-Worldwide-at-End-of-2017.html`.

[2] Kushal Shah, Philip Martinez, Emre Tepedelenlioglu, Shaddi Hasan, Cedric Festin, Joshua Blumenstock, Josephine Dionisio, and Kurtis Heimerl. An investigation of phone upgrades in remote community cellular networks. 2017.

[3] List of lte frequency bands. `https://en.wikipedia.org/wiki/LTE_frequency_bands`.