EmergeNet: Robust, Rapidly Deployable Cellular Networks

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***Abstract*—Cellular phone networks are often paralyzed after a disaster, as damage to fixed infrastructure, loss of power, and increased demand degrade coverage and quality of service. To ensure disaster victims and first responders have access to reliable local and global communication, we propose EmergeNet, a portable, rapidly deployable, small scale cellular network.**

In this article, we describe EmergeNet, which addresses the challenges of emergency and disaster areas. EmergeNet provides free voice calling and text messaging within a disaster area, and enables users of unmodified GSM handsets to communicate with the outside world using the Skype Voice over IP (VoIP) network. We evaluate EmergeNet's ability to provide robust service despite high load, limited bandwidth, and software or hardware failures. EmergeNet is uniquely well suited to providing reliable, fairly allocated voice and text communication in emergency and disaster scenarios.

***Keywords*-Cellular networks, community cellular networks, emergency networks, GSM, solar energy, wireless networks**

I. Introduction

Cellular telephony is the most widely adopted communication technology on the planet. There are more than 6.8 billion active cellular subscriptions worldwide, with half of those subscriptions added in the last five years, largely in developing areas [1]. In many developing areas, cellular networks have leapfrogged traditional landline telephone and Internet infrastructure, due to the comparative ease and low cost of deployment.

Investments in cellular network infrastructure are often concentrated in urban areas and along transport corridors. The combination of low population density and lack of reliable infrastructure makes commercial-grade cellular network deployments largely unprofitable in rural areas. As a result, low-density areas, rural areas, and areas with limited power infrastructure are largely underserved by cellular infrastructure.

Community cellular networks have emerged to address this coverage gap, offering economically sustainable cellular service in rural areas using low-cost cellular base stations. Recent deployments demonstrate the technological and economic feasibility of such networks. For example, UC Berkeley researchers operate a profitable cellular deployment in Papua [2]. Rhizomatica, a community-owned non-profit, operates five GSM networks in the Mexican state of Oaxaca, providing unlimited local calling and texting to residents for $1.20 per month [3].

Cellular base stations deployed by community cellular networks can cost under $10,000, while a large cellular carrier might spend $100,000 or more to deploy a base station. A complete cellular base station can be constructed with only a few components: a Linux PC, a software defined radio, a power source, an amplifier, and an antenna. Open source software running on each base station, such as OpenBTS, handles Um interface communication with GSM devices, and translates GSM calls and text messages to Session Initiation Protocol (SIP) messages. Telephony software, such as FreeSWITCH, enables users to make and receive calls, send and receive text messages, and access interactive services through voice calls or text messages. Community cellular networks use IP infrastructure, such as Wi-Fi networks and the Internet, for communication between base stations and with the rest of the world.

As it turns out, many of the characteristics of a successful community cellular network are also essential for emergency and disaster networks. We define emergency and disaster networks (EDNs) as communication networks used by first responders and victims of disasters. Both types of networks operate under challenging power and network backhaul conditions. Both must be easy to deploy, operate, and maintain. EDNs have the additional requirements of serving large numbers of users, dealing with attempted usage in excess of network capacity, and operating in rapidly changing networking environments.

EDNs are used to provide local communication inside a disaster area and enable contact with the rest of the world. These networks may use pre-existing wireless infrastructure, or first responders may build and deploy a network as part of their recovery efforts. Often, it will be a combination of both, as all available avenues for connectivity are explored. EDNs are rapidly evolving networks, as additional hardware is added, backbone infrastructure is restored, and users migrate from network to network. One example of an EDN, the Red Hook Wi-Fi network in Brooklyn, NY, went from serving dozens of users to more than three hundred users per day after Hurricane Sandy impacted the area [4]. The performance of the network was impacted as usage exceeded network capacity. As the network's importance as a community information hub grew, the network was expanded to include additional Wi-Fi access points and a satellite backhaul connection from the Information Technology Disaster Resource Centre [5].

Emergency and disaster networks that incorporate GSM cellular base stations have several advantages over non-cellular EDNs. A single cellular base station can cover a radius of up to 3 kilometers, providing a coverage area equivalent to dozens of Wi-Fi access points [6]. GSM handsets are ubiquitous worldwide, and while Wi-Fi devices are very popular, Wi-Fi does not yet have the global market penetration of GSM, particularly in the developing world. This makes cellular-based EDNs an ideal means of providing communication services to a large percentage of the world population, and providing wireless coverage to large areas without extensive hardware deployments.

Lack of reliable power infrastructure, a chronic problem in developing rural areas, can paralyze cellular infrastructure in even the most well-developed areas after a disaster. Following Hurricane Sandy, the FCC reported approximately 25% of cell sites in the affected 10-state area were non-operational [7]. Commercial cellular base stations require access to network operator services such as a mobile switching center and home location register. Damage to central switching stations, power outages, or loss of backhaul connections can eliminate cellular service across large areas. Community cellular base stations do not require any remote infrastructure to operate, and are therefore better suited to emergency and disaster use.

In this work, we leverage a rural community cellular network, VillageCell (also called Kwiizya), as a starting point for a rapidly deployable cellular system for emergency and disaster networks [6], [8]. Importantly, we augment VillageCell to make it suitable for EDNs, by introducing features to enable inbound and outbound calling and messaging, handle high load, and enable automatic reconfiguration to address changing power and networking scenarios. We call this new solution EmergeNet. Our core contributions in this work are:

- Providing inbound and outbound VoIP calling and messaging to EDN users with unmodified GSM handsets.
- Designing an SMS-based call queuing system to provide fair access to voice services during periods of high load.
- Enabling automatic reconfiguration of cellular base stations to maximize functionality in the face of power, network, and hardware failures.

We begin by describing VillageCell, the community cellular network on which EmergeNet is based. We then discuss the limitations of VillageCell base stations as components of an emergency and disaster network, which inform the design of EmergeNet. We address these limitations with the design and implementation of EmergeNet, a community cellular network for emergency and disaster use. Finally, we evaluate the performance and effectiveness of EmergeNet as a means of communication in emergency and disaster networks.

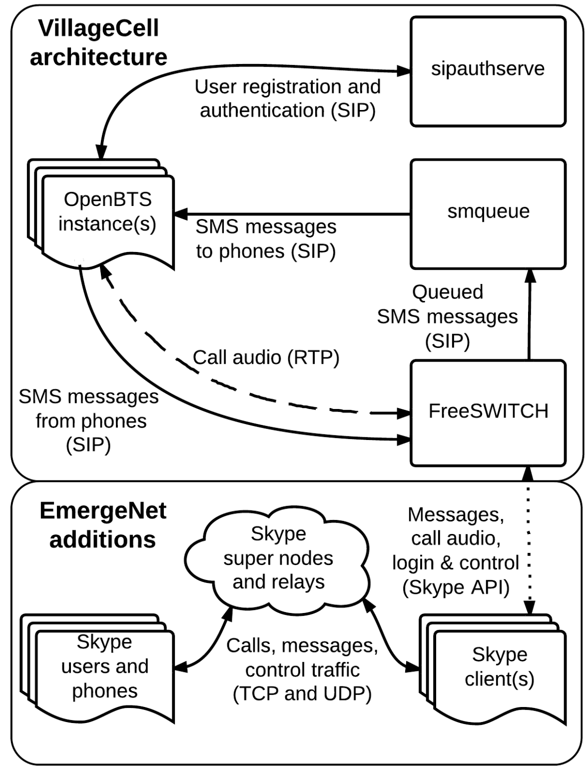

Figure 1. Architecture of VillageCell and EmergeNet.

II. Introduction to VillageCell

VillageCell is a low-cost community cellular network designed for rural areas, based on open source software and low cost hardware. VillageCell was designed to allow local users to communicate by voice or SMS with other local users for free. A VillageCell deployment, such as our trial deployment in Macha, Zambia, consists of one or more cellular base stations linked together using a Wi-Fi network [8]. Our previous work revealed that technological communication in rural areas most often occurs between users who live in the same village [9], [10]. By using several cellular base stations to provide GSM cellular coverage to large areas of a village, VillageCell enables local users to communicate with each other.

A. Operation and Design

Each cellular base station in a VillageCell network consists of a Linux PC with a software defined radio, running OpenBTS. Additionally, one VillageCell base station in each network must operate three required network services: sipauthserve for user management and access control, smqueue for queuing and delivering text messages, and the FreeSWITCH PBX for routing calls and text messages. Figure 1 shows the interactions between each of these software components in a VillageCell network. Figure 1 also shows EmergeNet's integration with the Skype network, which will be described in the next section.

OpenBTS is an open-source program that uses a software-defined radio transceiver to communicate with standard GSM mobile phones. OpenBTS can operate in the 850, 900, 1800, or 1900 MHz range. OpenBTS handles all communication with GSM handsets, which occurs on the GSM Um interface. OpenBTS converts GSM messages into equivalent Session Initiation Protocol (SIP) messages, and sends SIP messages (such as registration, call initiation, and text messages) to sipauthserve or FreeSWITCH. OpenBTS listens for incoming SIP messages, and converts them to GSM transmissions on the Um interface. OpenBTS also encapsulates GSM voice calls into Real-time Transport Protocol (RTP) audio streams, suitable for switching by FreeSWITCH. The design of OpenBTS ensures FreeSWITCH, smqueue, and sipauthserve do not need to communicate over the Um interface to interact with GSM phones. Instead they send SIP messages to OpenBTS. This greatly reduces the complexity of communicating with GSM devices.

When a user enters the coverage area of the VillageCell network, their phone may connect automatically to a VillageCell base station. Most GSM handsets will roam on any available GSM network if their home network is not available. If commercial cellular service is available, the user will stay on their home network unless they manually select the EmergeNet network in their phone's settings. As GSM handsets perform no authentication of GSM base stations, the EmergeNet base station may provide service to all mobile users, without any a priori information from cellular operators about their customers.

When a VillageCell user calls another user, OpenBTS receives GSM call establishment messages from the phone, converts them into a SIP message, and sends it to FreeSWITCH. FreeSWITCH routes call requests and bridges the call's RTP audio stream to the recipient's OpenBTS base station. When a VillageCell user sends a text message, the SMS message is received by OpenBTS and sent to FreeSWITCH for processing. This allows SMS applications to be implemented as scripts called by FreeSWITCH when a message is received. To deliver text messages to GSM handsets, FreeSWITCH sends the text message to smqueue, which makes a best effort delivery to the OpenBTS base station where the recipient is registered.

B. *Limitations of VillageCell*

While VillageCell is ideally suited for rural environments, it has a number of important limitations in the context of emergency and disaster networks. These include the existence of single points of failure, capacity limitations, and a lack of connectivity to the rest of the world, which we describe in more detail below.

1) Single points of failure: The vulnerability of VillageCell to single points of failure is exemplified in the specific trial deployment in Macha, Zambia. In this deployment, the base station hosting FreeSWITCH, sipauthserve, and smqueue was struck by lightning. The base station's network connection was rendered nonfunctional. The remaining functional base stations did not receive responses to the SIP packets they were generating as users attempted to place calls and send messages. Because FreeSWITCH did not respond, calls were not connected and messages were not sent, even when both users were connected to the same OpenBTS base station. Any network failure impacting the main base station, or failure of the main base station itself, rendered the entire network unusable.

2) Capacity limitations: Each of the cellular base stations deployed in Macha is a Range Networks Snap Unit, consisting of a Linux PC and a RAD1 software defined radio with 1 ARFCN (Absolute Radio Frequency Channel Number). Each base station can support about 15 registrations per minute, 40 text messages per minute, and 7 concurrent calls [11]. When a base station reaches the maximum number of concurrent calls, further call attempts result in the call being rejected due to congestion. VillageCell does not make any special considerations for operation under particularly high demand, which can negatively impact the user experience.

3) Inbound and outbound communication: VillageCell was designed to facilitate local communication. As such, it does not include support for calling or texting out of the VillageCell network. In a post-disaster environment, communication with the outside world is critical. Disaster victims and first responders will seek assistance from outside the impacted area, by contacting aid groups, friends and family, insurance agents, response coordinators, and other remote people or groups.

III. EmergeNet

We use our experience with VillageCell to introduce EmergeNet, a community cellular network architecture designed for robust performance in emergency and disaster networks. We augment VillageCell to make it suitable for EDNs, by introducing features to enable inbound and outbound calling and messaging, handle periods of high load, provide for rapid deployment, and enable automatic reconfiguration to mitigate the impact of power, network, and hardware problems. The following sections explain each of these features in more detail.

A. *Inbound and outbound communication*

While VillageCell focused on providing free local calling and texting, EmergeNet addresses the need for bidirectional communication with the rest of the world. We enable 'inbound' calling and text messaging, which originates from any phone or Skype user in the world and terminates at a

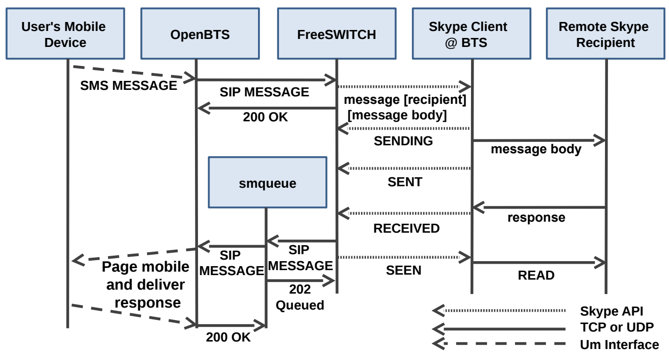

Figure 2. Messaging between a GSM phone user and a Skype user.

cellular phone connected to an EmergeNet base station. We also allow for 'outbound' calling and text messaging, where communication originates in the EmergeNet network and terminates at any Skype user or phones in 170 countries. We have developed VillageVoIP, a set of software tools that runs on a cellular base station and enables inbound and outbound calling and messaging through Skype.

VillageVoIP allows anyone with a GSM handset to use Skype, which usually requires an Internet connection and a smartphone or PC. We do not require end users to possess any software on their device. Instead, we run a Skype client for each user on an EmergeNet base station. To minimize resource consumption, each Skype client is launched using a virtual X window session, and a 'fake' sound driver. Users control their Skype session by sending SMS messages to the base station.

The SMS interface to Skype has five commands:

1) login [username] [password]: Starts a Skype session for the specified Skype account
2) logout: Terminates the user's Skype session
3) friends: Sends the user an SMS listing their online Skype contacts
4) chat [recipient] [message]: Sends a text message to the recipient
5) call [recipient]: Initiates a Skype call to the recipient

VillageVoIP uses scripts launched by FreeSWITCH to interact with users via SMS or voice calls. Figure 2 shows a round trip SMS message flow between a user's phone and a remote Skype user. The user's outbound SMS message is passed from OpenBTS to FreeSWITCH, then parsed by a python script. The python script uses the FreeSWITCH endpoint mod_skypopen to pass Skype API commands to Skype clients from within FreeSWITCH. When inbound Skype communication is received, python scripts within FreeSWITCH pass chat messages to smqueue for delivery to users via SMS, or trigger a voice call by sending SIP messages to OpenBTS. If a user logs into their own Skype account, inbound chat messages and Skype calls will automatically be routed to their cellular device. If a user does not login to their own Skype account, their outgoing chat messages and calls originate from a shared Skype account.

Calling any Skype user or toll-free numbers in many countries, including Australia, France, Germany, the United States, and Taiwan, is free. This will enable an EmergeNet user to contact friends, family, coworkers, and nonprofit organizations without charge. Usage of non-free Skype features, such as calling landline phones, will be automatically billed to the logged-in user's Skype account.

B. Handling periods of high load

Previous experiments have shown that as SMS message load increases on OpenBTS platforms, delay in sending or receiving SMS does not substantially increase [6]. SMS messages are asynchronous, and typically are automatically retried by the user's handset if not immediately sent. Therefore, queuing or congestion are unlikely to negatively impact a user's SMS experience.

In an emergency situation, it is nearly guaranteed that attempted usage of each EmergeNet base station will exceed seven concurrent calls, the maximum call capacity of EmergeNet's OpenBTS system. Once this limit is reached, further call attempts will result in the call terminating seconds after dialing. Thus the limit on concurrent calls, if not addressed, will lead to a negative user experience in an already stressful situation. It will also lead to an increase in congestion as users repeatedly retry their calls.

We mitigate this issue by creating a queue for voice calls. If demand for voice calls exceeds the base station's voice call capacity, each additional call request is placed in a first-in-first-out queue, and the caller is informed of their place in the queue via SMS. A script monitors channel availability and CHANNEL_HANGUP_COMPLETE events generated by FreeSWITCH, and connects calls in the queue as channels become available. This prevents users from having to repeatedly retry their calls.

C. Rapid deployment

EmergeNet is designed to be rapidly deployed anywhere in the world. EmergeNet can be deployed as a stand-alone system including the cellular base station, a solar power system, and a satellite Internet backhaul. Alternatively, EmergeNet nodes can be deployed in coordination with aid organizations, relying on shared or pre-existing power and network infrastructure.

Each EmergeNet base station includes an AC adapter and a DC buck-boost converter, to ensure EmergeNet base stations can be powered from any 100-240V AC or 4-32V DC power source capable of providing 30W of power. This includes vehicle batteries, portable generators, and power grids. To ensure these power connections can be made, each EmergeNet base station includes a 12V vehicle power port connector, plug adapters compatible with AC outlets in over 150 countries, and battery terminal clamps.

If operation from solar power is desired, each EmergeNet node can include four 100W solar panels and three 100 Amp-hour 12V non-spillable sealed lead acid (SLA) batteries. This solar power configuration is designed to provide 24/7/365 uptime in most locations. Due to the low power consumption of EmergeNet nodes (<30W), the battery bank will provide a minimum of four days of runtime without sun. The solar array is sized to fully recharge the battery bank with one day of sun in latitudes within 30 degrees of the equator. The solar power system is modular and can continue operating even if several of the solar panels or batteries are stolen, damaged, inefficiently deployed, or relocated to support other infrastructure. Additional solar panels can be added for deployments in regions further from the equator, or as weather conditions require.

We selected our batteries with rapid deployability as a key consideration. While many batteries are subject to limitations on transport, non-spillable SLA batteries are not considered hazardous if they comply with the International Air Transport Association Dangerous Goods Regulations Section 4.4, Special Provision A67. This permits EmergeNet nodes to be shipped worldwide with batteries installed. We have traveled with SLA batteries on US-based and European air carriers without incident.

By using Skype to route inbound and outbound calls and messages, EmergeNet supports voice calling and text messaging to and from phones in 170 countries, with no country-specific configuration required. This is particularly important for enabling rapid deployment worldwide. Using Skype to access the public switched telephone network eliminates the need to configure SMS and VoIP interconnects in each country EmergeNet is deployed, and for each country EmergeNet users want to call. Finding reliable and functional interconnects was a primary challenge faced by Heimerl et al. in Papua. In this work, researchers evaluated tens of SMS-routing companies, and determined that "an exhaustive search for the correct partner will be required whenever deploying in a new country" [2]. EmergeNet's design eliminates the time and labor intensive task of setting up and evaluating VoIP and SMS interconnects.

EmergeNet is designed to be easily deployed by one or two people with limited technical knowledge. With an EmergeNet node in the bed of a pickup truck, a successful deployment should take less than 10 minutes, and consist of only a few steps:

- Park the truck facing north, to provide maximum solar radiation for the south-facing solar array in the bed.
- Raise the antenna mast.
- Align satellite antennas or long-range Wi-Fi antennas based on the current location.
- Power on the base station.

EmergeNet nodes can operate independently, or in coordination with each other. Each EmergeNet node will periodically check for the existence of other EmergeNet nodes on the local network. If an EmergeNet network is found, new nodes will automatically join the pre-existing EmergeNet network. Otherwise, the node creates its own EmergeNet network. This process requires no human intervention and is further explained in the next section.

D. Automatic reconfiguration

A core design goal of EmergeNet is to offer graceful service degradation in place of failure. Each cellular base station will react to problems with other EmergeNet nodes or the local network infrastructure. In systems with more than one base transceiver station (BTS), each BTS evaluates the availability of its neighbors and will reconfigure itself accordingly.

We use monit, a process monitoring daemon, to increase the reliability and robustness of each cellular base station. Monit monitors the availability of the base station's services, as well as the availability of the main BTS and neighboring BTS units. Monit automatically restarts failed software components and proactively prevents the base station from entering error conditions, such as filling the disk or running out of memory. We configure monit to check the status of all services every 10 seconds, which is frequent enough to detect failures rapidly, and uses at most 0.2% of the base station's CPU and memory. More frequent monitoring may increase writes to disk and network traffic, while less frequent monitoring lengthens average downtime due to failure.

Many community cellular networks, including VillageCell, rely on a central PBX, such as FreeSWITCH, to route calls and text messages. When this PBX is not available, SIP messages from OpenBTS to FreeSWITCH will not receive responses. Without responses from FreeSWITCH, OpenBTS loses all functionality. Users cannot place calls or send text messages, even to users on the same BTS.

To allow any base station to quickly take over the role of main BTS, each EmergeNet base station is capable of acting as the 'main BTS', by launching sipauthserve, smqueue, and FreeSWITCH. We configure OpenBTS to send SIP traffic to a floating IP address, which is not owned by any specific machine on the network. This allows one or more base stations to claim the floating IP and take over the role of main BTS, enabling rapid recovery from base station or network failures. Each base station will periodically check whether the main BTS is available. When the main BTS is unreachable, the base station will check whether higher-ranked base stations are accessible. If they are, the base station waits for one of the higher-ranked base stations to become the main BTS. If no higher ranked base station is available, the base station claims the floating IP address, advertises the route change to the network, and becomes the main BTS. Traffic will automatically be rerouted to that base station. This ensures that even when network connections

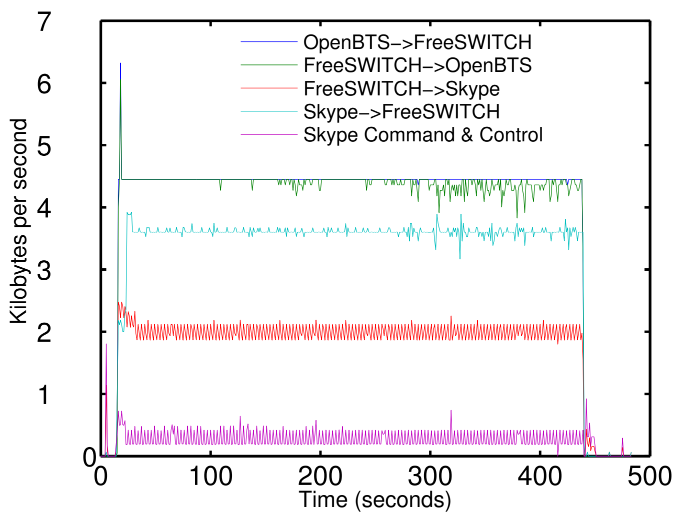

Figure 3. Network Utilization for one Skype call.

	Local Network	Uplink	Downlink
Skype call	8.6 Kb/s	2 Kb/s	4 Kb/s
Local call	8.6 Kb/s	0	0
SMS to Skype	1.4 - 1.6 Kb	2.9-3.7 Kb	1.4-1.7 Kb
Skype to SMS	1.4 - 1.6 Kb	1.1-1.9 Kb	1.7-2.9 Kb
Local SMS	2.8 - 3.2 Kb	0	0
Registration	1.52 Kb	0	0

Table I
BANDWIDTH UTILIZED BY EMERGENET ACTIVITY.

	Time to detect	Total downtime
OpenBTS failure	<1 second	20.2 seconds
FreeSWITCH failure	10.4 seconds	24.6 seconds
smqueue failure	6.1 seconds	6.5 seconds
sipauthserve failure	6.3 seconds	6.4 seconds
Main BTS failure	61.6 seconds	106.3 seconds

Table II
MEAN TIME TO DETECT AND CORRECT FAILURES OVER 10 TRIALS.

between base stations fail, each base station continues to route calls and messages locally and to any reachable BTS.

IV. EVALUATION

In this section, we explore the suitability of EmergeNet for emergency and disaster networks, and demonstrate EmergeNet's rapid recovery from failure.

A. *EmergeNet network traffic evaluation*

To evaluate EmergeNet's performance on the network level, we performed several calling and messaging experiments. We developed an Android application which programmatically sent messages and placed calls from ten mobile devices camped on two EmergeNet base stations. We captured all network traffic at each base station using tcpdump. As shown in Figure 3, each traffic stream was classified based on its endpoints, revealing the traffic impact of each EmergeNet component. We measured the bandwidth consumption of each EmergeNet feature, averaged over 10 calls, registrations, or messages. For messaging tests, we performed each experiment twice, using the minimum (1 character) and maximum (160 characters) SMS message length.

As Table I shows, EmergeNet nodes are well suited to operating in EDNs with limited bandwidth backhaul connections and congested local networks. When calling remote users, each Skype call uses only 2 Kb/second on the backhaul link for outbound voice traffic, and 4 Kb/second for inbound voice traffic. Skype background traffic, such as presence notifications and peer selection, consumes less than 1 Kb/second per user on average. A standalone EmergeNet system generates no additional local network traffic, since OpenBTS, FreeSWITCH, smqueue and sipauthserve all operate on the same machine and communicate via the loopback interface. In networks with multiple EmergeNet base stations, communication between EmergeNet components generates small amounts of traffic on the local network, which connects EmergeNet base stations to each other. Voice packets passed between base stations use RTP over UDP. Therefore, packet loss on the local network will impact the audio quality of calls, but EmergeNet nodes can continue operating on lossy networks without negatively impacting the local network with useless retransmissions of audio packets.

B. *Rapid recovery*

EmergeNet nodes monitor their services and performance, in order to maintain the availability of service and decrease downtime. We evaluate EmergeNet's robustness and rapid recovery by inducing an error condition, then measuring the length of time before the error is detected and service restored. For the OpenBTS, FreeSWITCH, and Main BTS failure tests, we consider service restored when an EmergeNet GSM handset can send a Skype chat message to a remote Skype user. We consider smqueue and sipauthserve functional when they respond to SIP messages on their respective ports.

The system takes less than two minutes to go from 'off' to 'operational'. As Table II demonstrates, EmergeNet nodes are unlikely to face downtime lasting more than two minutes. The average time to detect a failure in sipauthserve or smqueue is, generally, just over half monit's 10 second polling interval. Failures in FreeSWITCH could take two polling intervals to be discovered, as the FreeSWITCH process may appear functional while shutting down. Unlike the relatively simple sipauthserve and smqueue, OpenBTS and FreeSWITCH require initialization before they begin functioning properly. This is reflected in the longer recovery time for those components, 20.2 second and 24.6 seconds respectively. In the event of main BTS failure, the network waits about one minute to permit the main BTS to recover from its failure and restore service. In the worst-case scenario where the main BTS cannot recover, a second base station takes over the IP address of the main BTS, launches all required services, and becomes the new 'main BTS'. This process takes roughly 45 seconds from the time failure is detected, resulting in downtime of 106.3 seconds on average.

V. Conclusion

EmergeNet provides disaster victims and first responders with a robust, portable, rapidly deployable cellular telephony system. The EmergeNet cellular network is affordable, low power, and provides voice and text messaging services to wide areas. We utilize the Skype VoIP network to enable free and low cost calling and messaging to Skype users and phones in over 170 countries, and show that this Skype traffic does not over-utilize EDN backhaul connections or local networks. EmergeNet is an improvement over traditional hierarchical cellular networks in emergency scenarios, as it has no reliance on carrier infrastructure, which is often damaged in disasters. We believe EmergeNet's model of self-contained cellular base stations using standard IP networking to connect to each other and the Internet will prove to be extremely robust in emergency and disaster scenarios.

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