# 30 Years of Wireless Ad Hoc Networking Research: What about Humanitarian and Disaster Relief Solutions? What are we still missing?

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## ABSTRACT

In the event of a disaster, the communication infrastructure can be partially or totally destroyed, or rendered unavailable due to high congestion. However, during such crisis situations, there is an acute need for information exchange for both rescue organizations and victims. Temporary communication solutions are thus of utmost importance until the infrastructure is restored.

In this paper, we start by reviewing communication solutions – stemming from 30 years of research on ad hoc, mesh and delay-tolerant networks – able to uphold communications during disasters when the communication infrastructure is destroyed, overloaded or not existing in the first place. We present how these solutions can be applied and summarize the advantages and disadvantages of each unique approach. In a second part, we present, Twimight, a Twitter application relying on delay-tolerant opportunistic communications to spread tweets and sensor data in an epidemic fashion. Twimight is an open source Twitter client for Android phones featured with a "disaster mode", which users enable upon losing connectivity. In the disaster mode, tweets are not sent to the Twitter server but stored on the phone, carried around as people move, and forwarded opportunistically when in proximity with other phones. Eventually, we demonstrate how opportunistic technologies such as Twimight can be of great value right after a disaster by enabling the self-organization of victims and a better coordination with first rescue organizations. We discuss the main challenges to overcome and provide directions for future research both non-technical (e.g. user adoption of technology) and technical (e.g. security and data privacy).

## Categories and Subject Descriptors

A.1 [**Introductory and Survey**]; C.2.1 [**Network Architecture and Design**]: Wireless Communications

## General Terms

Design, Security

## 1. INTRODUCTION

Communication systems such as wire-line, cellular and fixed/mobile broadband telecommunication services have become an integral part in modern society. In the event of man-made or natural disasters (i.e. the 9/11 terrorist attacks, hurricane Katrina, the Queensland floods, the Fukushima nuclear disaster, etc.), these communication systems may be wiped-out (earthquakes, floods), overloaded (surge of traffic and flash crowds) or not existing in the first place (developing countries).

Information and communication are the cornerstone of any disaster response for informed decision-making. They enable organizations to collaborate to avoid gaps and overlaps in the concerted response; coordinating emergency services personnel, requesting aid from medics and for victims to contact missing family and friends.

This acute need for information exchange, for both rescue organization and victims, requires the set up of temporary communication solutions until the regular infrastructure is functioning again. A study by Gisli Olafsson [1] on how ICT played a role in the 2011 Pakistan flood response and how information management was utilized during the response concludes that nothing much has evolved since 2005 (and the response to the Pakistan earthquake). Only connectivity has improved but only slightly. The communication technology of responders varies from phones and short-range AM radios to satellite links and self-contained networked Mobile Command Centers. NetHope and TSF, the two main crisis response organizations focusing on temporary telecommunication infrastructure rely on BGAN equipments and Network Relief Kit using a WiFi access point bridged to a satellite data link that can provide a local internet access.

These organizations are now considering using more recent technologies such as WiMAX or WiFi mesh networks. Nevertheless, two main issues remain. First, it is well acknowledged that the interoperability of communication equipments between organizations and even within the same organization is still a problem despite standardization efforts carried by the UN-OCHA through their working groups in telecommunications (WGET) and the Emergency Telecommunication Clusters (ETC). Second, temporary telecommunication infrastructures (i) are fully dedicated to relief coordination operations, (ii) cover only a limited range (e.g. WiFi AP) and (iii) are not usable by victims thus preventing victims to send short messages to their relatives or more advanced coordination efforts between victims and first responders.

Today's smartphones have the capability to communicate directly via Bluetooth or WiFi without requiring any supporting network infrastructure. This facilitates using opportunistic communications (e.g. P2P mobile communications) where alerts and messages spread epidemically from phone to phone, even in the harshest conditions.

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Opportunistic networking offers the possibility for victims to set up their own temporary network. And as soon as first responders arrive on site and set up temporary telecommunication infrastructures, traffic can be exchanged to and from the Internet and the disaster area by relying on people's smartphone to relay data outside of the temporary radio coverage. Opportunistic networking could be used within and between organizations until an infrastructure is put in place.

In this paper, we first review in Section 2 recent advances in the field of communication that have potential for disaster situations. We highlight the technological underpinnings and limitations of each solution. In Section 3 we will present, Twimight, our Twitter application relying on opportunistic communications to spread tweets and sensor data in an epidemic fashion. Twimight is an open source Twitter client for Android phones featured with a "disaster mode", which users enable upon losing connectivity. In the disaster mode, tweets are not sent to the online Twitter servers but stored on the phone, carried around as people move, and forwarded opportunistically via Bluetooth or WiFi Direct when in proximity with other smartphones. We will demonstrate how opportunistic technologies such as Twimight can be of great value right after a disaster by enabling the self-organization of victims and a better coordination with first rescue organizations in Section 4. We will also discuss the main challenges still to overcome and provide directions for future research in this emerging field from protocol and system design to security and data privacy.

# 2. SURVEY OF WIRELESS TECHNOLOGIES

We survey the technologies and supporting architectures that can provide communication services in disaster relief scenarios. We focus however only on works that have running prototypes or have been deployed. We highlight the technological underpinnings and limitations of each solution.

## 2.1 Classification

Disaster relief networking solutions may be classified under a number of distinguishing properties. For example, the protocol layer at which the solution operates, the support of local vs. global communication services, the reliance on infrastructure vs. infrastructure-less topologies, power consumption vs. communication coverage, etc. We have chosen to distinguish between cellular networks and wireless (WiFi-based) solutions. We have partitioned the broad class of wireless network solutions into wireless ad hoc, wireless mesh [2] and delay-tolerant opportunistic networks [3] [4]. We have termed a combination of different approaches wireless hybrid networks.

We give a brief summary of each networking solution below. Figure 1 illustrates our classification and the different solutions we will review next.

**Cellular networks.** GSM [5] and UMTS [6] provide a wide range of communication services to users with high spatial coverage. The coverage and quality of service provided by these networks surpasses that of wireless ad hoc networking solutions by design. Cellular networks leverage on a complex interconnection of spatially distributed, high power base stations to provide seamless communication coverage. Cellular networks, on the other hand, require significant infrastructure and attract high deployment and maintenance costs. Nevertheless, cellular networks are most desirable in a disaster relief situation where ubiquitous mobile phones can be utilized for fast and easy-to-use communication.

**Wireless Mesh networks.** Mesh networks are characterized by a collection of fixed and stationary wireless access-points interconnected in a mesh topology acting as the infrastructure. Wireless clients can then establish multi-hop communications over the mesh. The advantage of such a topology is the inherent redundancy between pairs of nodes and the coverage achieved through multi-hop communication. The main disadvantage is the setup time required to deploy such networks. One of the biggest mesh network providing Internet connectivity is operated by AirJaldi [7] in India spanning 70 × 30 km with only radio WiFi links.

**Wireless Ad-hoc networks.** Ad-Hoc networks consider an infrastructure-less network where devices can reach any other device through multi-hop routing over a dynamic topology. The main assumption behind ad hoc networks, i.e. end-to-end connectivity, is not realistic and has been relaxed with the more generalized form provided by delay-tolerant networks. We do not consider ad hoc networking solutions in this survey.

**Wireless Delay-tolerant Opportunistic networks.** Delay-tolerant networks are a class of infrastructure-less network where wireless nodes may not always be in communication range of each other and hence no end-to-end connectivity can be assumed. To enable reliable communication, new routing protocols [8] have a been devised which are invariant to the connectivity delays encountered in such networks.

**Wireless Hybrid networks.** In the context of disaster relief networking, there is attempts to bridge-the-gap between cellular networks and wireless networks. Combining the topologies found in both these technologies introduces a hierarchical structure that can enhance communication coverage and quality of service during the transition phase of disaster response. Wireless hybrid networking solutions have the potential to provide several smaller population regions with communication services where wireless mesh technologies alone are limited by range, and where cellular infrastructure is unavailable or incompatible.

## 2.2 Enabling Disaster Management Systems

Disaster management systems (e.g. Red Cross DMIS) are the primary user of wireless emergency communication solutions. These systems rely heavily on maps as a vital tool to create a shared picture of the emergency. They help in directing aid and to avoid gaps and overlaps in the concerted response between different organization and NGOs. With the Web 2.0 revolution, new platforms have taken a very different approach to crisis management and coordination.

The Ushahidi [9] project, for instance, has developed an open source web-based platform [10] for collecting, sharing and visualizing information on maps. The concept behind the platform is crowd-sourcing; an open call to a group of people to report on a story or situation. Using this anonymous method of information collection, the "truth" of a reporting is not guaranteed, however, with a high enough volume of reports, the underlying truth of such reports begins to emerge. Citizens in a crisis situation can send reports to the Ushahidi web-server detailing the situation, which in turn warns fellow citizens of danger and spreads awareness of the crisis worldwide. The Ushahidi platform uses the mobile phone as its primary means of communication, utilizing web, email, SMS or MMS to submit reports.

Ushahidi has proven to be a successful online platform for spreading awareness of crisis situations worldwide. However, its limitation in disaster relief communication lies in its strong dependency on cellular network and/or Internet connectivity. In a typical disaster scenario, fixed and wireless communication systems are likely to be unavailable, thus preventing the operation of the Ushahidi application. We will see later how opportunistic communications, similar to those applied in the Twimight application, could be included to provide localized reporting features in a disaster scenario.

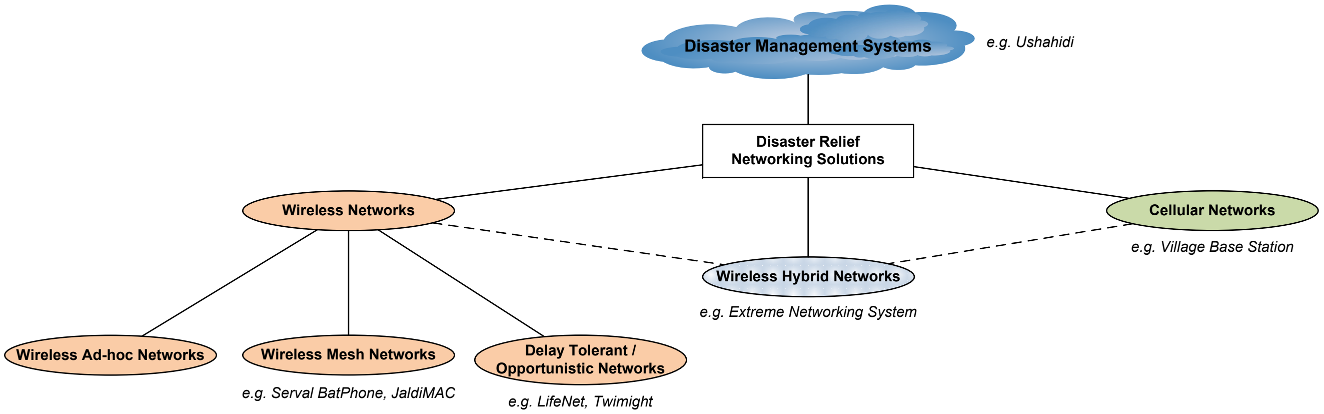

Figure 1: Classification of disaster relief networking solutions to support disaster management systems.

## 2.3 Cellular Networks

While the GSM Association is pushing for more resilient GSM base stations [11], especially for operators in disaster-prone regions, there is still a need for deployable cellular networks in case the infrastructure has been wiped-out or destroyed.

**Village Base Station (VBTS)**. Heimerl *et al.* [12] have implemented a cost effective, low-power GSM cellular base station, named the Village Base Station (VBTS). Although their solution is targeted for telephony services in rural areas and developing countries, their solution may also be deployed for disaster relief networking. The VBTS consists of an outdoor PC executing an instance of a software defined radio [13] that implements a low-capacity GSM base station. The software-defined GSM protocol stack is interfaced to a full-featured software private branch exchange (PBX), providing voice and data switching services to the localized GSM cell. The VBTS architecture has the flexibility to support a range of local telephony services including voice, data, SMS and voice messaging. Global telephony services may be achieved by connecting the VBTS to a backhaul network using long-distance WiFi or WiMAX links.

The VBTS features a low-power consumption (approx. 20W), making it possible to operate off-the-grid, meaning alternative energy sources such as solar or wind may be used in the absence of mains power. The low-power operation is achieved by providing intermittent coverage of the GSM cell through power duty-cycling. The power saved through intermittent coverage is used to boost the total coverage area when in operation.

The VBTS architecture leverages on the ubiquitous availability of low-cost GSM mobile handsets, making their solution well suited for telephony in both developing countries and in disaster relief situations. However, the intermittent coverage of the VBTS is a limitation in disaster relief operations where continuous cellular coverage over of the disaster zone is most desirable. This limitation may be mitigated using additional power sources (i.e. diesel generators and battery banks) supplied by the disaster response forces. Currently, the VBTS can only be used for voice communications and does not support 2G data communications yet.

## 2.4 Wireless Networks

**Serval Project** The Serval Project [14] is believed to have developed the first practical mesh mobile telephony platform, called the BatPhone. The Serval BatPhone aims to supplement infrastructure-based telephony systems with a device that is infrastructure-less, thus making the adoption of mobile telephony in rural and low-economic regions cost effective. The BatPhone's independence on existing telephony infrastructure also makes it favorable to disaster relief networking.

The Serval system comprises of WiFi-enabled Android smart phones, each configured in 802.11 ad hoc mode and interconnected in a mesh topology using the BATMAN [15] mesh routing protocol. Each BatPhone handset maintains a unique subscriber identity (SID) comprising of cryptographic primitives for encryption and authentication purposes. The existing phone number of the handset may be conveniently claimed by the user, thereby assigning the number to the BatPhone's unique SID. Multiple phone numbers can be assigned to the same SID, providing the option to create telephony gateways to fixed or mobile phone operator networks. Each BatPhone handset selects an IP address randomly from an address space, thus providing a mapping between the claimed phone number, the SID and the IP address of the handset.

Voice over IP (VoIP) services are initiated between calling parties by broadcasting a resolution request for the callee's phone number to all nodes in the mesh network. If a response is returned, the IP address and SID is revealed to the caller and the Session Initiation Protocol (SIP) establishes a VoIP call over the mesh network. In the event a callee does not have the BatPhone application installed, the software may be duplicated from phone to phone.

The Serval BatPhone has great potential for use in disaster relief situations. Although the range of WiFi point-to-point links is limited, the multi-hop connectivity of a mesh network coupled with support for real-time voice services is a advantageous. There is however a power consumption vs. coverage trade-off, since battery power from each BatPhone handset along the mesh path is being used to relay voice traffic destined for other users. There also exists a limited network bandwidth upon which all simultaneous VoIP traffic must be supported on. The question of how the power consumption and available network bandwidth for each BatPhone scales in a crisis situation, where several calls coexist simultaneously, is open for further research.

**LifeNet**. If we relax the high-throughput and low-latency communication requirements, we can achieve reliable connectivity under transient conditions using delay-tolerant networks and protocols. One example of routing protocol for such networks is packaged in LifeNet by Mehendale *et al.* [16]. Their ad hoc routing protocol uses a new routing metric, termed *reachability*, that captures the effects of transients within a network. The reachability metric from a source to destination measures the end-to-end probability that a packet transmitted at the source reaches the destination over all possible paths. The reachability metric is evaluated by sending a series of broadcast packets with the Time-to-Live (TTL) field in each broadcast packet decremented at each node, before being diffused further into the network. The more well-connected (or reachable) a node is, the more copies of the broadcast packet the node receives. Based on this assumption, the routing algorithm decides only to forward packets to nodes that are well-connected, as this choice will more than likely forward the packet to the intended destination.

The routing protocol in LifeNet is independent of the underlying MAC/PHY layer, making it applicable to a wide range of ad hoc WiFi-enabled devices. The disadvantage is that due to the reduced bandwidth and increased latency under transient conditions, this routing protocol is only suitable for low-bandwidth data services such as short messaging or social media applications.

**Twimight**. Hossmann *et al.* [17] have developed a smart phone application, Twimight, incorporating opportunistic communication techniques for peer-to-peer, delay-tolerant, messaging in disaster scenarios. They have augmented the popular Twitter social media application with a "disaster mode", enabling the communication of tweets to neighboring mobile phones without the need for contacting online message distribution servers.

Twimight uses delay-tolerant epidemic routing [8] to exchange tweets between users, when they are in close proximity of one another. The detection of nearby Twimight users is performed by periodically scanning for reachable Bluetooth devices. When connectivity to the online Twitter servers is re-established, all tweets stored locally on the phone are sent (retweeted) to the online server. Twimight has been further extended to tweet captured sensor data sampled from built-in mobile phone sensors (i.e. microphone, accelerometer, gyroscope, etc.). The disseminated sensor data gives further information about the user's environment, which could serve as a "sign of life" in a search and rescue scenario. Eventually, Twimight has been extended with security features [18] and a Twitter Disaster Server (TDS) providing similar security features (authentication, confidentiality, accountability) for the delay-tolerant epidemic spreading of tweets as with the classical online access.

The Twimight application is a very easy-to-use, low-bandwidth, and delay-tolerant application for disaster relief communication. The underlying assumption is that all affected users with a smart phone have the application installed, which in reality may not be the case. Extending Twimight to support dynamic software propagation would facilitate fast application deployment in a crisis situation.

**Technology and Infrastructure for Emerging Regions (TIER)**. Since 2004, the TIER group is working on wireless networks to bring affordable Internet access to rural communities in developing countries. Their architecture considers long-distance WiFi links to interconnect different WiFi hotspots. It is well known that the performance of 802.11 WiFi links is poor over long-distances [19]. The unsynchronized Carrier Sense Multiple Access (CSMA) scheme employed in the 802.11 MAC exhibits high collisions, and hence reduced performance, as the distance between nodes increases. Ben-David *et al.* [20] have proposed a MAC-layer solution to this problem, named JaldiMAC, which provides high-performance point-to-multipoint long distance links using the 802.11 physical layer.

JaldiMAC utilizes a Time Division Multiple Access (TDMA) scheme between a master and a collection of station nodes. Allocation to the wireless channel is coordinated through the master's scheduler, with time synchronization maintained by polling at each station. The TDMA schedule is partitioned into a scheduling horizon termed a window, where a number of rounds are scheduled within each window. Each round consists of a contention slot, followed by uplink and downlink slots allocated for each station. Assuming all stations can hear the master, each station acts accordingly on the allocated time slots. Each station time slot is allocated dynamically during the previous round, while new stations may request bandwidth during the contention slot at the beginning of each round. Acknowledgement packets are handled efficiently using a bulk acknowledgement scheme.

The long-distance performance of JaldiMAC and its use of the ubiquitous 802.11 PHY make it well suited for establishing last-mile communication links between WiFi devices in a disaster scenario. The polling nature of the TDMA scheme is not well suited for low-power hand-held devices (i.e VoIP phones). However, it would be feasible to implement JaldiMAC in gateway access points, which could interconnect small clusters of devices over long distances. Directional antennas and elevated positioning of the gateway access points would further increase coverage area.

## 2.5 Wireless Hybrid Networks

**Extreme Networking System (ENS)**. Braunstein et al. [21] deployed a hybrid network architecture for the support of a medical emergency response application in San Diego. The hybrid network consisted of three hierarchies; a WiFi network, a wireless mesh network (using CalMesh [22]), and multiple backhaul networks (i.e. wired/wireless/cellular/satellite). A number of gateways were used to interconnect each layer in the hierarchy, providing a distributed network with high reliability and availability.

The ENS architecture was tested during a homeland security drill, where several challenges were encountered. High interference in the 2.4GHz ISM band was observed from a neighboring video broadcasting source, which adversely effected the performance of the WiFi-based networks. The client/server-based medical emergency response application functioned poorly under intermittent delays and network partitioning. It was also found that deploying the hybrid network with an optimized topology is nontrivial. The overall network topology was found to be dependent on prior planning, the terrain of the disaster zone, the target application and how the response actions are ordered.

The ENS deployment highlighted the influence of network planning, protocol and application selection on the overall hybrid network performance. Disasters are near impossible to predict, making their planning across all possible terrain combinations exceedingly difficult. Therefore, rather than trying to optimize the topology during a rapid emergency deployment, the routing protocols employed on each network element in the hierarchy must be robust enough to cope with sub-optimal network topologies. Furthermore, the applications supported over the hybrid network must be robust against intermittent latency, bandwidth constraints and dynamic topology changes. Despite the challenges encountered by the ENS deployment, the concept of deploying a hierarchy of spatially distributed networks in a phased response to a disaster has significant advantages in terms of availability, redundancy and security.

# 3. TWIMIGHT - OPPORTUNISTIC TWITTER

In this section we provide a brief overview of the architecture of Twimight with the main focus on the disaster mode and the opportunistic spreading of tweets[1]. We have implemented *Twimight* as a disaster ready Twitter client in Java for the Android operating system. Figure 3 gives an overview of the two modes of operations, normal and disaster, which we detail next. *Twimight* accesses user

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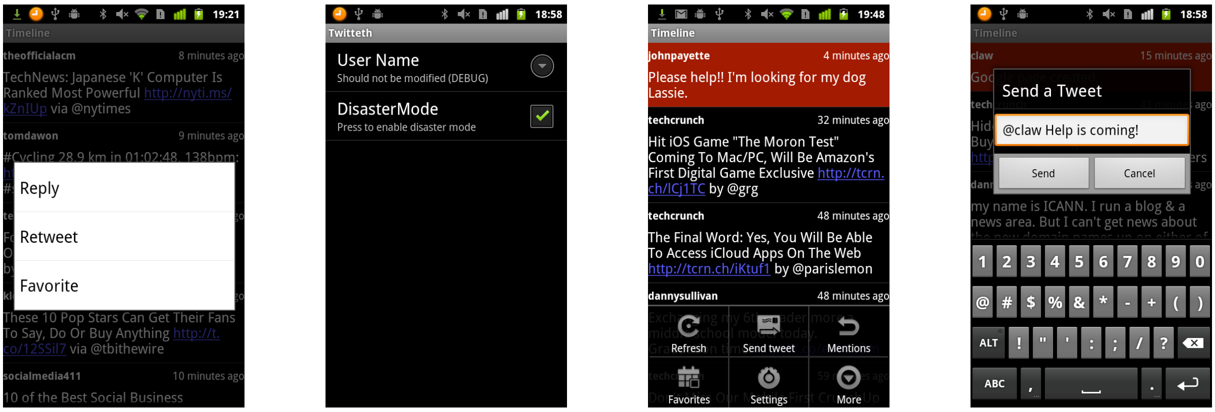
[1] For a more detailed discussion of Twimight functionality see also [17].



theofficialacm 8 minutes ago
TechNews: Japanese 'K' Computer Is Ranked Most Powerful http://nyti.ms/kZnIUp via @nytimes

tomdawon 9 minutes ago
#Cycling 28.9 km in 01:02:48, 138bpm:

These 10 Pop Stars Can Get Their Fans To Say, Do Or Buy Anything http://t.co/12SSil7 via @tbithewire

socialmedia411 10 minutes ago
10 of the Best Social Business

User Name
Should not be modified (DEBUG)

DisasterMode ☑
Press to enable disaster mode

johnpayette 4 minutes ago
Please help!! I'm looking for my dog Lassie.

techcrunch 32 minutes ago
Hit iOS Game "The Moron Test" Coming To Mac/PC, Will Be Amazon's First Digital Game Exclusive http://tcrn.ch/lCj1TC by @grg

techcrunch 48 minutes ago
The Final Word: Yes, You Will Be Able To Access iCloud Apps On The Web http://tcrn.ch/iKtuf1 by @parislemon

dannysullivan 48 minutes ago

claw 15 minutes ago

@claw Help is coming!

my name is ICANN. I run a blog & a news area. But I can't get news about

(a) Normal timeline and tweed context menu.

(b) Enabling disaster mode.

(c) Timeline with highlighted disaster tweet.

(d) Sending tweets in disaster mode.

Figure 2: *Twimight* screenshots.

data using OAuth and the Twitter API after the user grants access to *Twimight* by logging in with its Twitter credentials.

**Twimight in Normal mode**: *Twimight* supports most basic Twitter functionality like showing a timeline (i.e. the most recent tweets of the followed users), sending tweets, re-tweeting and replying to and setting favorites, direct messages etc. In normal operation, *Twimight* queries Twitter for new tweets every 2 Minutes. The tweets obtained from the queries are cached locally in a SQLite database. Figure 2a shows the timeline in normal operation and the actions a user can take.

**Twimight in Disaster mode**: *Twimight* has a checkbox in the settings menu to enable the disaster mode as shown in Figure 2b. The normal Twitter client functionalities stay the same but now rely on opportunistic communications. Upon enabling the disaster mode, the tweets of the user are internally assigned the special status of *disaster tweets*. They are stored locally in a separate table for opportunistic spreading and later publication to the Twitter servers whenever connectivity is detected. Compared to the normal mode of operation of Twitter, disaster tweets are sent epidemically and are thus public to everyone. Disaster tweets are highlighted in red on the user interface (Figure 2c) to mark them as important regardless of the receiver being one of the sender's followers or not. The goal is that all tweets sent during a disaster can be received and displayed to as many people as possible.

In disaster mode, the device enables Bluetooth and maintains the CPU awake acquiring a wake lock to constantly listen to connection requests from other devices. Further, it scans periodically for reachable Bluetooth devices. The scanning interval has been set to 2 minutes $\pm U[0, 20]$ seconds. It represents a trade-off between energy consumption and delay as a longer scanning interval would miss short connection opportunities. The interval has been randomized in order to avoid scanning collisions (i.e., two devices always scanning at the same time will never see each other). Once two phones have discovered one another, they connect to each other and exchange the new disaster tweets, thereby spreading them epidemically. We choose Bluetooth for opportunistic communication, because in spite of its limitations (cumbersome pairing, etc.), it offers an acceptable trade-off between battery lifetime and service provided. Another big benefit is that it can be used without rooting the Android devices. Adding alternative ad hoc communication methods such as WiFi Ad Hoc and WiFi-Opp [23] is planned for the future.

**From Disaster to Normal mode**: As soon as connectivity to the Twitter servers is re-established, the disaster tweets sent (or re-tweeted) by the user are published to the Twitter server. Publishing only own tweets avoids duplicate publication and authorization issues.

# 4. TOWARDS CROWD DISASTER RELIEF

In this Section, we first demonstrate that opportunistic networking is feasible in practice and then, through a typical scenario, we show how Twimight can be of great value right after a disaster by enabling the self-organization of victims and a better coordination with first rescue organizations. We conclude with research directions in this emerging field of digitally-enabled relief or relief 2.0.

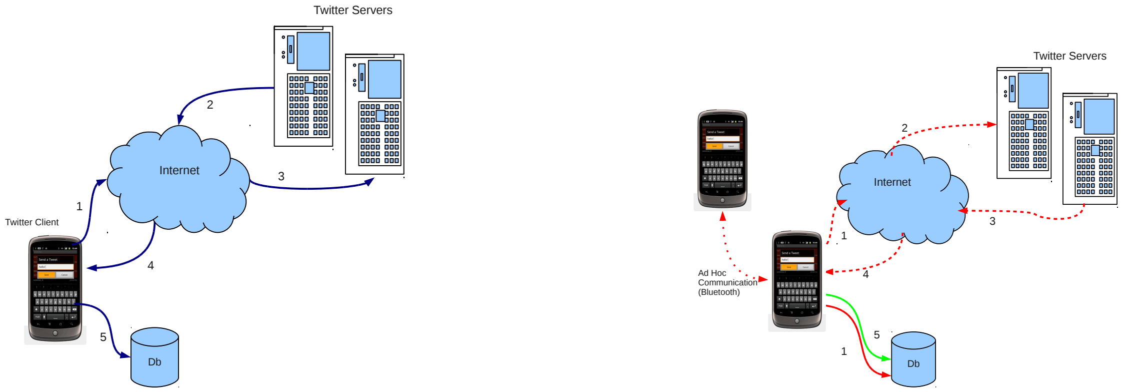
## 4.1 On the feasibility of Opportunistic Networking

A study on human spatial connectivity using mobile phone usage [24] provides a convincing empirical argument towards the use of wireless ad hoc networking for connecting large populations. Using an extensive set of mobile phone connectivity records, the study investigated the influence of contact distances on the construction of giant population clusters. The empirical evidence suggested that giant population clusters are in fact constructed from the interconnection of many smaller population clusters, where contact distances of as little as 50 meters can span up to 7% of the total population. This result gives an indication of the population connectivity assuming low to medium contact distances, which are achievable with current wireless ad hoc technologies (WiFi Ad Hoc, WiFi Direct, ZigBee). We can assume that mobility will allow bridging the different disconnected clusters required for information to spread. Eventually, we would like to stress that current ad hoc technologies have limitations on current mobile OSes (e.g. required device pairing, no ad hoc support), which would prevent to fully exploit the potential of ad hoc communications. We have developed WiFi-Opp [23], a more open standard than WiFi Direct.

## 4.2 Leveraging the Crowd

The question now is how to leverage the crowd during a disaster, at early stages. We sketch an imaginary disaster scenario seen from the perspective of a victim and then from the perspective of a response team. We show how Twimight can be of great value in both cases.

Assume a disaster scenario, as it happened in Japan in 2011, where a gigantic earthquake was followed by a tsunami. Such a disaster leaves thousands of deaths and ten times more homeless. Family members are separated and isolated from each other. Some



(a) Normal operation.

(b) Disaster mode operation.

Figure 3: Two modes of operation. Continuous blue lines mean normal operations. Dashed red lines refer to attempts in disaster mode, whilst continuous red lines means operations that are performed without problems in disaster mode.

of them escaped to safe places while others may be stuck in demolished buildings. The fixed telecommunication infrastructure is fully or partially wiped out, including the cellular systems and fixed line Internet access. Even the surviving communication infrastructure quickly becomes congested by the information storm that follows on a disaster and may run into a halt. The power infrastructure may as well be completely down. Roads and rails are partially or completely destroyed and may be only usable for emergency vehicles.

**Victim's perspective**: In the first few hours after the disaster happens, distressed people try to comprehend the situation they find themselves in and to locate their family and friends.

A survivor of a disaster will find himself, in the best case, with a mobile phone but without any cellular coverage. Neither placing a phone call nor sending a text message is possible. Without cellular infrastructure, social networks such as Facebook and Twitter do not work either. Finding an operational landline phone or a computer with Internet access is hopeless because of power outage. Yet, there is battery energy in the phone that can be used for opportunistic communication with other phones over WiFi and Bluetooth in the local area. Also, the satellite based GPS positioning is working and people can therefore obtain their exact position.

In our scenario, Mr. Survive, activates the disaster mode on his phone. The phone detects that there is no infrastructure and therefore switches on opportunistic networking via WiFi or Bluetooth. Social media now run in distributed mode without server support. Mr. Survive first wants to locate his family members and therefore sends tweets asking about the location and well-being of his relatives, geo-tagged with his current position. As he moves around, looking for them, these messages spread epidemically from phone to phone. If a recipient of a tweet has relevant information (e.g. received tweets from Mr. Survive's family members) she replies to it and potentially helps to reunite them. Mr. Survive will do the same for others. Eventually, he receives messages from his family members that they are safe with their positions.

After he knows that his family has survived he wants to understand where he could get help. He wants to know where there is fresh water, distribution centers of food, where he can charge his phone, safe shelters and other primary needs. This information is opportunistically exchanged with other people he meets and eventually matched with messages that offers what he is looking for and the position of the facilities. Mr Survive also decided to subscribe to tweets about disaster news and weather forecasts to get a better understanding of the larger situation.

While he is moving his way through debris he may also find some injured victims, groups of people trying to dig their way through demolished buildings to rescue locked survivors, etc. All of these scenes can be recorded by the phone's camera and, tagged with the location, be important information for first rescue teams. After the first rescue teams arrive and set up temporary Internet connections, the messages will be uploaded to social networks where also off-site relatives and friends see that Mr. Survive is ok.

Further, after meeting the rescue team he was given a water sensor that could differentiate between fresh, polluted and hazardous water. While wading through water drenched terrain his sensor continuously collects information about the water quality and detects areas of hazards. This information and the precise locations are collected by the smart phone and the positions of hazard water as well as type of pollutions are tagged. When Mr. Survive got the alarm about the water he also decided to take a picture of the area that is also attached to the tag. This information is then opportunistically distributed to other people that he meets so that they get a warning if they are approaching the area. A map of the water hazards will also assist emergency teams in their efforts and priorities.

**Response teams' perspective**: When first response teams arrive at the location of a disaster site, they have two initial tasks before the actual rescue missions can start: (i) to gain an overview of the current situation, the extent and severity of the disaster (number and location of affected people, etc.) and (ii) to coordinate among themselves, and with their back offices.

As a very first step, the response team has to establish information about already ongoing help efforts and other teams which are potentially already in place. For this purpose, they use temporary telecommunication infrastructure (JSAT, BGAN, Network Relief Kit) and the Information Kiosk as a central coordination point where all response teams place reports. Checking in to the Information Kiosk reports their presence and location to other response teams. At the same time they learn about other teams on site and their reports and progress with the rescue mission. This gives a first indication about where their help can be most efficient.

Once their presence is established, the team has to gain as much information about the situation, as quickly as possible. Besides directly talking to people in the area, Twimight is a second means for collecting information and efficiently establishing the bigger picture. Affected people on site have already tweeted reports, locations, pictures from all around the area and these reports start flowing in as soon as the team arrives. Based on this first information, as well as offline maps of the location, satellite images, and all available information, the team can decide where to build their base and place temporary telecommunication infrastructures.

Having a localized temporary telecommunication infrastructure serves two purposes. First, it provides a channel through which the opportunistically spread messages can reach the social networks and hence victims can inform their relatives and friends about their well being. Second, it allows the response team feeding back information to the affected citizens: they can send tweets to the opportunistic network informing the people about the location of shelters, field hospitals and clear water sources. This information will again spread epidemically and reach people even if they do not obtain it directly from the response team.

## 4.3 Future Research

It is evident from our survey of disaster relief networking that multiple technologies need to be combined in order to encompass all phases of disaster recovery, while providing differentiated levels of communication services. For example, during the initial self-organization phase, delay-tolerant and opportunistic networks have the capacity to provide low-bandwidth data services, while wireless mesh networks have the availability and redundancy to provide limited voice and data services. During the latter response forces phase, cellular networks bring the capacity and coverage to support voice and data services over large distances. During the transitional phases of disaster response, wireless hybrid networks can be built through the interconnection of small network clusters, thus providing scalable communication support. Due to the heterogeneity of these wireless technologies, there are significant interoperability challenges which will continue to be a focus of future research.

There are many non-technical challenges faced by disaster relief networks. One such example is the adoption and usability of technology in the event of a disaster. However, leveraging on the popularity and easy-of-use of social media platforms, such those used in the Twimight application, these non-technical barriers begin to breakdown. A possible extension to Twimight is to support dynamic software distribution, which would help to automate application distribution in a disaster situation. This is a simple feature that could be easily added to current mobile OSes. Also to support illiteracy and distressed victims, user interfaces need to be carefully designed [25].

The issue of security has had little attention in the context of disaster relief networking. The confidentiality, integrity and availability goals of computer security are also applicable to disaster relief. For example, in the context of a terrorist attack, without adequate encryption and source authentication primitives an adversary may snoop and/or insert false crisis information. An attacker may even go as far as jamming the wireless communication channel. The sampling and presentation of data involving citizens in rescue operations will also require serious considerations of user privacy. The systemic use of encryption, authentication and anonymization will be important. Finding the optimal tradeoffs between data openness, availability and privacy will be a challenge. Eventually, people should be held accountable for their actions during a disaster. Victims should be aware that even during crisis and disaster situations, their actions can be traced back if need be. Further research would propose and evaluate security architectures applicable to disaster relief networking. We have provided a first answer in our security architecture for Twimight [18].

# 5. CONCLUSIONS

In this paper, we have presented a wide range of wireless networking solutions for disaster relief. We have investigated disaster relief networking solutions using wireless WiFi-based, cellular, and wireless hybrid network technologies. We characterized the solution technologies with respect to their suitability to the different disaster response phases; namely the self-organization phase, the response forces phase, and the transition between the two phases. It is evident from our evaluation that no single networking technology can encompass all phases of disaster recovery, which suggests that a combination of inter-operable networking technologies be used for disaster relief networking. We have demonstrated that opportunistic networking holds a great potential to enable the self-organization of victims. Combined with a social networking platform such as Twitter, we believe that we can provide the ideal communication emergency kit to victims of disaster. As highlighted, there remains significant research challenges in the field of disaster relief networking in terms of network architecture, protocol design, application development, network interoperability, and security. We, as researchers, need to help the humanitarian sector and especially the rescue organizations to avoid missing the next communication revolution that lies under opportunistic networking. This definitely requires advocating for our work but also getting involved, which is primary motivation behind any humanitarian commitment.

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