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Editors: Aruna Balasubramanian and Lin Zhong

SUPPORTING RESILIENCE IN RURAL EMERGENCY PREPAREDNESS AND RESPONSE THROUGH IMPROVED INFORMATION ACCESS

Recent disasters have highlighted the gap between existing urban-centric resilience models and the needs of rural communities, which are frequently marginalized. Large rural constituencies, encompassing vast and sparsely populated areas, lack broadband connectivity and rely predominantly on volunteer-based emergency workforce. The above are some of the key factors hampering rural first responders' ability to access, act upon and disseminate emergency-related information. This has an adverse effect on both residents and the agencies that serve them, as it limits residents' ability to prepare for emergencies and compromises the safety of first responders. Furthermore, the unique socio-economic structure of rural areas makes them particularly vulnerable to the effects of incipient or unfolding disasters. Hence, rural communities often develop self-reliance capabilities by creating tight-knit social structures and taking charge of their own technological progress through community-driven efforts.

Our work focuses on minimally invasive technological support that harnesses the inherent social and technological infrastructure in rural areas to provide improved access to critical information and aid emergency preparedness and response. To this end, we have partnered with rural communities and first responder agencies in the Adirondacks region of Upstate New York. Collaboratively, we are investigating the emergency information needs of residents and first responders and the underlying socio-physical infrastructure to inform the design of (i) the *E!App*, a smartphone application that leverages residents' social interactions for seamless dissemination of emergency information; and (ii) the Data Mule Unit, which allows first responders to remain connected as they move through community TV White Spaces networks and to deliver targeted information to rural residents. This paper describes our early experiences in co-designing and developing the E!App.

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While the United States critically relies on its rural areas for sustenance, the emergency preparedness and response (EPR) capabilities in these areas significantly lag behind those of their urban counterparts [9]. At the heart of the problem is lack of connectivity, which limits the capabilities for EPR information access for both first responders and residents, making rural areas particularly vulnerable to disasters. Improved information access can help first responders to make better decisions for taskforce dispatch and enhance the self-reliance of local residents during emergencies. In addition, different disasters require heterogeneous and even conflicting EPR strategies, further straining the capabilities of already overburdened rural first responders. For example, while natural disasters such as recent hurricanes and fires displace populations into shared and densely populated facilities, other disasters, such as the current COVID-19 pandemic, necessitate that people self-isolate in their homes. In either case, responders have to obtain and deliver timely information to their constituency. It is, thus, of critical importance to develop communication and information access capabilities that allow both information exchange through social interactions, and information delivery in the face of social distancing to equally cater to heterogeneous emergency scenarios.

EPR Information Access: Effective emergency preparedness and response of residents requires access to both static instructional information and dynamic alerts pertaining to unfolding emergencies. Some examples of static content include first aid/resuscitation tutorials [1], hazmat guidelines [2] and fire safety tips [3]. The true value of such information stands out in an incipient emergency. With regards to emergency alerts, various national [4, 5] and state [6] outlets provide contextual information about dangerous conditions. At the county/town level, local officials share targeted emergency preparedness and response information with their constituency through websites, smartphone applications and social media outlets.

However, creating rural EPR information access capabilities faces significant challenges:

Poor or lacking mobile broadband connectivity. To receive EPR information, residents are required to proactively subscribe to web-, email- or smartphone-based services, all of which require mobile broadband access. Rural areas, however, are characterized with spotty or non-existent coverage. 97% of the U.S. is categorized as rural, housing 19.3% (60 million people) of the overall population [19] of whom 30% (15.2 million) still lack mobile broadband access [20]. There is little expectation that these areas will be reached by commercial networks in the foreseeable future, as mobile operators find it hard to justify the low return on investment of building infrastructure in areas with sparse or impoverished population [21,22]. This lack of broadband in addition to aging and less technically versed populations, makes access to EPR information particularly challenging. First responders too increasingly rely on connected technologies, such as *IamResponding* [7], for coordination and information exchange. In rural areas, the lack of mobile broadband means that first responders can no longer coordinate or receive fresh information the moment they set out of the agency facilities, which further hampers the safety and efficiency of emergency personnel.

Shared resources and vast, sparsely populated areas. Rural areas are sparsely populated and often characterized by challenging terrain, which hampers access to reliable mobile broadband. In addition, individual towns often do not have their own first responder brigades (e.g. fire or medical services) or the necessary budget, and often rely on shared resources from other neighboring towns, the county, or state agencies [8]. This leads to additional challenges, as first responders have to travel tens of miles in rugged terrain and without Internet access to respond to an emergency. Concurrent emergencies due to prolonged disasters, such as the ongoing COVID-19 pandemic, are particularly straining to rural EPR, as the scheduling of limited workforce and resources becomes challenging. Thus, connected coordination on the fly and efficient information exchange between residents and first responders is essential.

Volunteer-based workforce. 95% of the fire workforce in rural U.S. is comprised of volunteers, whereas career firefighters make up 70% of the urban fire forces [9]. While career responders are often at the same locale (i.e., the fire station) when emergency unfolds, volunteers are typically scattered at their day jobs or their households. This makes efficient information exchange and coordination particularly challenging and important in rural areas.

Despite these challenges, rural areas, with their unique socio-economic composition, have demonstrated the ability and willingness to take charge of their technological infrastructure and progress [10]. Inspiring examples of community-led efforts span from building communications infrastructure to informing application design [11, 12]. In this paper, we leverage participatory design and technological innovation to address the gaps in EPR information access in rural disconnected communities, with an outlook towards sustainable innovation.

To this end, we develop the E!App (Figure 1, left), which caters to the information needs of rural residents and first responders. At the backend, the E!App serves as an information aggregator pulling from agencies at all levels – from the federal all the way to the local county and town level. This information is stored and curated

Photo, Patrick Dodson

FIGURE 1. E!App (left) and the Data Mule Unit (right).

at a centralized server and then delivered to E!App users through various modalities including direct Internet access, peer-to-peer exchange over Wi-Fi Direct and through a targeted dispatch aided by a Data Mule Unit (Figure 1, right). We pick Wi-Fi Direct as it currently provides the longest range for peer-to-peer communications on commodity mobile platforms, which we feel will better cater to the rural context of the E!App operation. By combining all these modalities, the E!App smartphone application is projected to cater to a multitude of emergency response strategies and situations, from socially engaged to socially distant.

Prior work on emergency applications either focuses on post-disaster response [13, 14], and as such tackles routing in multi-hop mesh networks for message passing applications, or on providing static instructional information related to emergencies [1, 2, 3, 15, 16, 17]. Several applications that connect users with both instructional information and alerts inherently assume that the users are continuously online in order to receive information [15, 16, 17]. Our work bridges these existing gaps by developing the E!App that can support the information flow from agencies to citizens both pre- and post-disaster despite limited communication infrastructure.

In what follows, we detail key consideration in rural emergency information access following a rigorous co-design process in collaboration with our partner community. We then describe the design and implementation of the E!App and discuss critical challenges towards the wide applicability of EPR information exchange over socio-physical networks.

KEY CONSIDERATIONS IN RURAL EMERGENCY INFORMATION ACCESS

The E!App is in its development stage. To cater to the emergency information needs of rural residents and first responders, we have undertaken a participatory co-design process, which is based on multiple focus groups with residents and first responders over the course of the past year. First, two focus groups were conducted with first responders to glean insights on what information they think should be delivered to residents and which are the most resourceful information outlets. Second, another two focus groups were conducted with residents to understand their emergency information needs. This information was used to develop a first version of the E!App, which was then demonstrated to residents in two more subsequent focus groups that were geared towards evaluating the usefulness of information types and presentation, interface functionality and design. In what follows we report key insights on rural residents' and responders' information needs.

Types of desired information. During our meetings with residents three dimensions of information needs emerged including severity, category and type of emergency. In terms of severity, residents differentiated between high, medium and low, and required the ability to customize the user interface (UI) for their desired severity of notifications. In addition, the residents differentiated between three categories of emergency information including (i) *preparedness*, which incorporates static instructional content, such as first aid tutorials, emergency food storage and shelter locations; (ii) emergency-related *news*, such as road blocks or seasonal fire restrictions, which may not be urgent but are of broader interest to the community; and (iii) *alerts*, which carry information about incipient or unfolding emergencies and may be urgent. Finally, residents wanted to receive different types of information, which could be thought of as related to different *types* of emergencies, including weather, fire, hazmat, medical, road conditions, school closures and police updates.

Intuitive and customizable user interfaces. The importance of intuitive UI was emphasized during our discussions. Residents also asked to be able to customize the type of emergency alerts that they receive. Such customization was desirable both across alert types and severity, as well as across geographical regions. For example, residents wished to be able to receive alerts for home when they travel and receive alerts for other locations where loved ones live. Residents also underlined the need to customize the UI features such as the color scheme of the app and the font size of the content. This was particularly important to elderly residents in our focus groups.

EPR information flows. Rural residents expressed interest in various directions of EPR information exchange. Trusting their agencies, they agreed that information flow in the direction from first responders to residents was important. However, equally important to them was the ability to use technology to exchange information within their tight-knit social networks. While appealing, the ability for resident-to-resident and resident-to-agency communication brought up some concerns. Resident-to-resident it was not clear where the liability for misinformation would lie. Similarly, in the resident-to-agency direction, a key concern to first responders was their inability to verify the trustworthiness of crowd-sourced information. This issue was further aggravated by the lack of staff to manage and curate crowd-sourced emergency information.

E!App DESIGN

To develop the E!App, we partner with the Town of Thurman and the Warren County Emergency Services Department. Warren County is at the foot of the Adirondacks mountains in Upstate New York. Thurman is in the county and as of the 2010 census it comprised 337 families. At 13 residents per square mile, Thurman is a typical American rural mountain town, making physical and online communication difficult. Due to lack of commercial broadband, the town had procured a grant through the NYS Broadband Initiative and has built a six-sector TV White Space network, which serves as a wireless backhaul for residential Internet access.

The E!App is a smartphone-based application that provides EPR information access to rural disconnected areas. The app includes two components: the E!App server and a smartphone application, which we detail below. The E!App system design is depicted in Figure 2. Inside a rural community we differentiate between three types of users: (i) Internet subscribers, (ii) not Internet subscribers but "social" and (iii) not Internet subscribers and not "social." The first type of users can obtain EPR information directly from the E!App server. The second can get their information through phone-to-phone exchange as they get in contact with other E!App users who have fresh data. Finally, E!App users who are neither Internet subscribers nor social can obtain their information through targeted dispatch aided by a Data Mule Unit (DMU) that travels through the community on responders' vehicles. We are currently working with our partners to identify which community services traverse the community most regularly and can serve as a reliable vehicle for information dispatch.

The E!App server works as an aggregator of emergency information and alerts from various sources identified in our focus groups. These sources currently include NOAA's weather service, NY511 Transportation Department Alerts, Warren County's Twitter and Facebook accounts and various preparedness articles from their websites. The scrapers execute every minute and package the received notifications into the server database. E!App users who come online query the database to receive fresh EPR information. Besides information aggregation, the E!App server also collects user encounter information, which is employed in modeling the community's socio-physical network. This model serves various purposes including (i) understanding hot-spots that can be leveraged for rapid P2P information exchange, (ii) detecting information-depleted sub-groups, which have to be aided by the DMU, and (iii) overall model for mobility, which allows for smart battery-aware decision making for when and where to scan for peers and exchange information.

The E!App smartphone application is an Android-based app, which serves EPR information to rural residents. Facing the user is an intuitive interface, which presents residents with EPR information split across categories (Preparedness, News and Alerts), types (Weather, Hazmats, Medical, Roads, Fire, Other) and severity (High, Medium and Low). A multi-pronged background process ensures maximal information access to all types of rural residents. Alongside proactive information access, the E!App also maintains continuous context sensing of Wi-Fi and Cellular networks availability and quality, E!App user encounters and users' geolocation in order to aid in establishing socio-physical models of rural communities.

Maintaining communication over socio-physical networks using mobile platforms requires hands-free information exchange

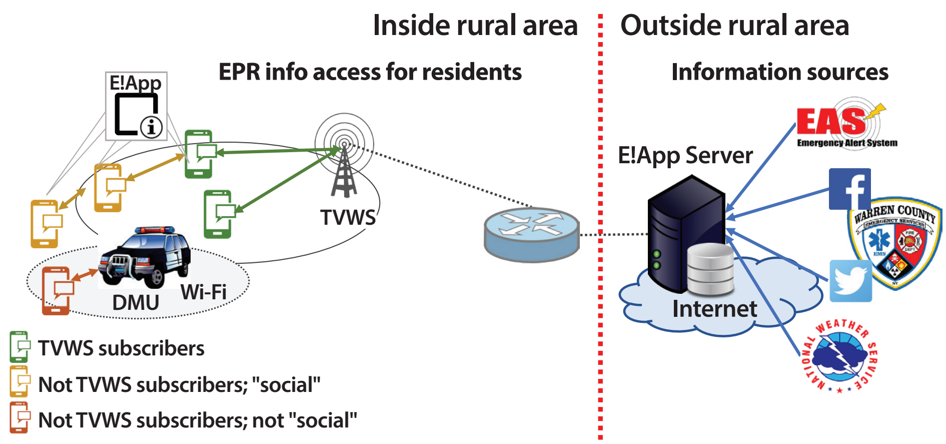

FIGURE 2. E!App system overview.

between users' devices; i.e., E!App devices should be able to discover each other and exchange information unbeknownst to the user. To this end, the app runs background services that periodically scan for other E!App devices and exchange EPR information. This intensifies a classical problem in mobile platforms between service availability and battery life. In Android, the so-called Doze Mode [18], was conceived in API v.23 from August 2015 and refined ever since towards increased efficiency in battery utilization. The inherent principle of Doze Mode is that as long as the user is not actively engaging with their phone, all background services and their respective access to networking and geolocation are halted. As such, emerging mobile platforms increasingly cater to interactive applications while staggering the progress of other services that do not require user engagement. In what follows, we discuss key components for enabling seamless information exchange in the E!App.

Ensuring trust and privacy in hands-free information exchange. For privacy reasons, Wi-Fi Direct requires explicit consent from all users whose devices will be exchanging information in a peer-to-peer network. Wi-Fi Direct supports persistent and non-persistent (standard and autonomous) groups. The latter requires user consent with every encounter and is, thus, not well-suited for hands-free information exchange. Persistent Wi-Fi Direct groups require user confirmation only upon the first encounter and thus, we opt for them in the E!App.

Synchronizing user interactions. To exchange information through a peer-to-peer network, E!App users not only have to scan for peers periodically, but their scan attempts need to be synchronized, so they can discover each other and exchange. To achieve such a synchronization, we implement a global clock with a pre-programed global start time, which is set for all users of the E!App. All scan events are scheduled periodically over this global clock. This behavior is illustrated in Figure 3 for two E!App users. We note that significant clock drifts on individual E!App devices may cause distortion of a user's view on the global clock. Android phones, however, can be set to automatically synchronize their time from a global server, which, as per our early experimentation, retains sufficient synchronization for successful user discovery. We also note that Wi-Fi-Direct peers sustain their scan procedure over a wide range of durations (Figure 4), with a median of 6 seconds, bottom 25th percentile of 1.2 seconds and top 25th percentile of 41.4 seconds. Thus, as long as phones are synchronized within this interval, peer encounters will continue to be successful.

Sustaining information exchange without requiring user interaction. Vital to the E!App's operation is its ability to perform scheduled information exchanges regardless of whether a user is engaged with their phone or not. The evolution of Doze Mode towards sustained battery life has made this increasingly challenging. To keep the E!App running, we exempt the app from battery optimization and use a combination of foreground services and setExactAndAllowWhileIdle() alarms.

E!App CHALLENGES AND LESSONS LEARNED

We design the E!App with an outlook towards wide adoption and equitable information access. For wide adoption, we develop the E!App for stock Android platforms without requiring any custom modifications (e.g., a rooted phone). To ensure equal experience in EPR information access for offline and online users, we tap into existing information sources, including social media and live alert systems. The lessons learned while following these design principles shed light on various shortcomings that elucidate the rural-urban technological divide in emergency preparedness and response.

Lesson 1: Mobile systems are not made for resilience. The usefulness of commodity mobile platforms is inherently dependent on their access to infrastructure (i.e., Wi-Fi and Cellular networks) and online services (e.g., Online Social Networks or Content Distribution Networks). Underlying capabilities, such as Wi-Fi Direct, that can aid resilience, are rudimentary at best and take non-trivial amount of effort in both development and troubleshooting to enable seamless information flow in peer-to-peer fashion. To realize the full potential of direct connectivity, mobile operating systems (OS) should support an Emergency mode, for which users can opt in, which inhibits aggressive battery optimization and allows for easy application access to underlying communication and geolocation resources. This can have long-lasting positive impact on disaster resilience, as it will incentivize the development of third-party peer-to-peer applications, creating a similar ecosystem as that for classical online client-server applications.

Lesson 2: Wi-Fi Direct on Android is not made for mesh data exchange. Wi-Fi direct is predominantly conceived with the idea of connecting "things" (e.g., smart TVs, etc.) to the Internet. As such, it supports one-to-one or one-to-many star topologies with the Group Owner (GO) in the center and all Peers connecting and exchanging through the GO. This is less than optimal from a maximized information exchange standpoint and, thus, the current Wi-Fi Direct implementation requires non-trivial application development to ensure information consistency across all collocated users. In the E!App, we tackle this by creating exhaustive lists of available peers and attempting to maximize one-to-one connections within a single duty-cycle. This adds to the battery cost in scanning and exchange.

Lesson 3: There is tension between privacy and usability. The E!App uses persistent Wi-Fi Direct groups, which inherently imposes a fixed hierarchy between peers, i.e., the roles of Peer and Group Owner from the first encounter are retained for any subsequent encounters. It is worth investigating how these dynamics affect the efficiency of communication over socio-physical networks.

Lesson 4: It takes two to tango. The peer-to-peer nature of the E!App inherently requires that two (or more) peers are at the same time and place in order to exchange. Our experience in developing the E!App has shed light on just how nuanced this collocation requirement is, as there are a series of factors stemming from the user, OS and network chipset behavior, and the environment, which underpin the success of peer-to-peer information exchange. Are peers collocated? Are their phones able to initiate a peer scan as prescribed by the app's global clock? Are the underlying networking resources accessible (i.e., the OS is not forcing Doze mode) and available (i.e., there are no other services currently contending for Wi-Fi access)? Will the group formation succeed? Will the encounter duration be sufficiently long for the exchange to happen? What is the degree of external interference? Understanding all of these factors and incorporating them in protocol design underpins the success of peer-to-peer information exchange.

Lesson 5: Modeling and incorporating spatio-temporal user behavior is crucial for the optimal battery life in E!App-like applications. While the E!App does not support it yet, it has become clear that establishing a hotspot model and using it

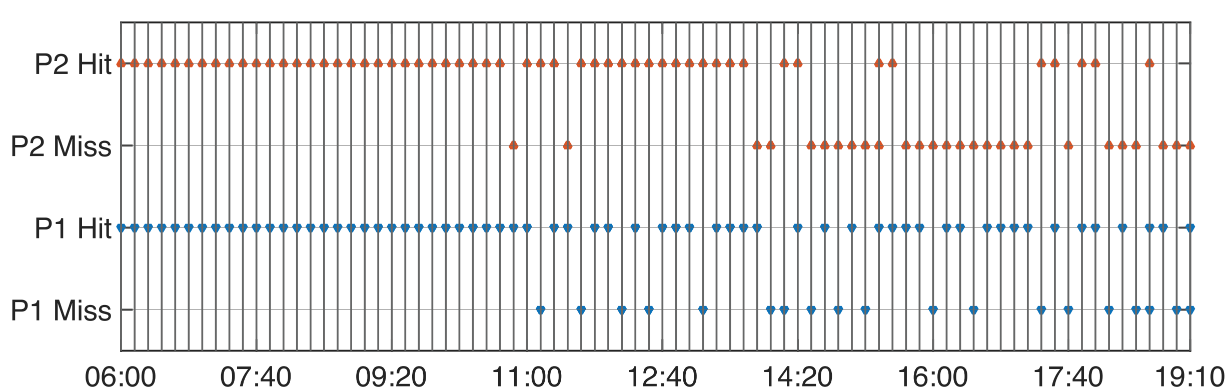

FIGURE 3. Scan events on two Moto G6 phones running the E!App in close proximity for the duration of 15 hours. The app duty cycle is scheduled to execute every 10 minutes (black vertical lines). Scan initialization events are indicated along the P1/P2 Hit horizontals. Scan initialization failures are indicated along the P1/P2 Miss horizontals.

to drive peer-to-peer exchange decisions is crucial for preserving battery life, maximizing information exchange and ensuring high usability of the app.

Lesson 6: Not all EPR sources are designed for offline consumption. While most of the information in the Alerts category of the E!App is short and concise, Preparedness and News information typically comes over social media outlets and includes a short message with a chain of web links to be followed. Thus, scraping Preparedness and News information has to embed curation mechanisms to ensure that the scraped information is accessible and useful to offline users, who inherently cannot follow a chain of web links to get informed.

Lesson 7: The importance of keeping measurements untainted. Understanding the discrepancies between expected and actual application behavior often requires pulling data from multiple probes and across multiple versions of the same platform. We have explored a plethora of additional tools across all protocol levels including pcap captures[1], adb logcat[2], WPA supplicant[3] and vicinity sniffing with Alfa AC1900 Wi-Fi adapters. It is noteworthy that some of these tools require root access, while others require Wi-Fi or cable access to a PC. Cable access suspends battery optimization, hindering the ability to troubleshoot Doze mode issues, while Wi-Fi access uses the same chipset as that for Wi-Fi Direct communications, interfering with the observed success rate of peer-to-peer exchange. Root privileges replace the stock mobile OS with a custom one and, thus, may unlock benefits that would not otherwise be available on commodity unrooted phones (which are our target platform). Thus, the measurement approach may interfere with the application behavior and has to be accounted for in the analysis.

Lesson 8: Motivation of end-users to engage in the co-design process is key. Despite conveying the benefits of resident involvement in the E!App design, bootstrapping community participation was challenging. Beyond discussing the benefits in a general meeting, a close follow-up process was also needed to guarantee continued participation. Understanding the end-users' perceived value of the E!App, the general perception of local public affairs, conflicts in time schedules, and awareness about the project, were key to boost participation. Further, we learned about the importance of recruiting more participants with diverse backgrounds, to widely advertise co-design activities. Finally, we understood the importance of preparing potential participants, who are typically not involved in design processes, and to spend time building trust between end-users and the project team.

Lesson 9: The importance of actively engaging the community. Close collaboration with the community became an important part in planning and implementing the co-design process as well as in gaining support for the deployment and testing process. In the E!App development, collaboration with the Town of Thurman and the Warren County Emergency Services Department helped the project team identify and gain access to the right participants for the focus groups. The Director of the Warren County Emergency Services Department played a key leadership role not only to initiate the co-design process but also to provide strong support for future deployment and testing. However, it is not always easy to keep the community's commitment to be an active actor in the project. Conflict and tension in local politics and changes in the leadership may lead to the loss of interest and top management support. As a result, it is important to take context into account to maximize collaboration with the community.

Lesson 10: Useful and easy to understand approaches have a greater impact. Once participants have been recruited, facilitation of the co-design activities is the next important step to keep the participants engaged in the development of the E!App. Multiple design tools, such as games, visualizations, and/or probes, may be used to solicit participants' inputs and to inspire their insights about certain problems and possible solutions. During the development of the E!App, an Android emulator that visualized the functions and interface of the E!App seemed a more effective approach than simple tools like a slide presentation or whiteboard. It helped participants materialize future application of the app and provided a useful basis for their discussions on the needs for emergency information and app interface. The project team members played an important role as facilitators to guide participants through the various phases of the co-design session. Moving forward, more sophisticated design tools, like design games or service mapping, may be used to further facilitate engagement and to inspire new perspectives.

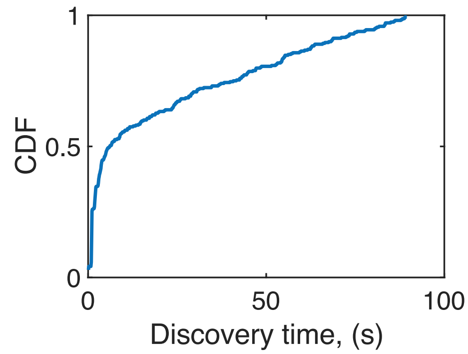

FIGURE 4. CDF of peer discovery time for a Moto G6 over 300 runs. The discovery time presents the duration for which the chipset attempts to find peers before it gives up.

Lesson 11: An iterative process to gain and evaluate inputs from multiple perspectives. Co-design is not a one-time activity, but a highly iterative process of planning, recruitment, and facilitation. These iterative processes are essential to explore and understand the underlying issue from a multi-actor perspective. In the E!App development, each iteration required some adjustments in recruitment and facilitation approaches that took into account different types of participants and previous experiences. In addition, an iterative process also happened in the back-end development as the project team needed to add participants' inputs and repeatedly reflected on the original design task, or problem definition, alongside the different solutions. Several rounds of open dialogue

[1] tPacketCapture is one example: https://bit.ly/2TACZ9A. For Wi-Fi Direct on an unrooted phone it is only useful for transport-layer analysis.

[2] https://developer.android.com/studio/command-line/logcat

[3] https://source.android.com/devices/tech/connect/wifi-hal

between the project team and the partner community were essential to assess the feasibility and realization of users' ideas into implementable solutions.

SUMMARY

This article described the design and implementation of the E!App – a smartphone-based application that leverages community infrastructure and socio-physical networks for improved access to emergency preparedness and response information in rural areas. We outlined key considerations for the E!App of residents and first responders following a rigorous co-design process. We also detailed key opportunities and setbacks in employing smartphone-based technologies for improved rural emergency preparedness and response. Most of the challenges outlined in our work will generalize across applications that seek to employ rural socio-physical networks, including environmental monitoring, remote healthcare and education. ■

Acknowledgements

This work is supported through an NSF Smart and Connected Communities award CMMI-1831547. We thank our collaborators Fred Engelmann and Lynn Engelmann from Rainmaker Networks, Cynthia Hyde, former Town Supervisor of the Town of Thurman, Brian LaFlure, Director and Fire Coordinator for Warren County Emergency Services Department, and the numerous members from the Fire and EMS agencies, and the Thurman community who participated in our focus groups.

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