Towards a Socio-Technical Framework for Bridging the Digital Divide in Rural Emergency Preparedness and Response: Integrating User Adoption, Heterogeneous Wide-Area Networks, and Advanced Data Science

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ABSTRACT

In rural areas, emergency preparedness and response (ERP) could be greatly affected by the lack of access to technology and the Internet and, therefore, to timely and accurate information about a natural or human-made disaster. This paper proposes a socio-technical framework that integrates a potential technology solution, with optimization methods, and strategies for user adoption. We argue that in order to bridge the digital divide in rural ERP, all these factors need to be systematically considered and integrated into a comprehensive framework, which could guide potential implementation.

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1 Introduction

Large-scale emergencies both man-made and natural are increasingly producing devastating losses in terms of human lives as well as financial resources. US losses from weather-related disasters alone exceeded $1 trillion during the three decades between 1980 and 2011 [1], and such events are on the rise due to climate change [2]. Two of the biggest recent events, hurricanes Sandy and Katrina, claimed close to two thousand U.S. lives and resulted in more than $200 billion in losses [3]. Rural communities, with their social and economic composition, are uniquely vulnerable to emergencies both small and large-scale [4–6].

While the United States critically relies on its rural population for food [7], water and energy [8], the available resources and thus effectiveness of emergency preparedness and response (EPR) in rural areas still lag well behind their urban counterparts [4, 5]. EPR services increasingly rely on mobile broadband connectivity for timely information collection, integration and dissemination among stakeholders, including responder agencies, local governments and residents [10, 11]. While such technologies are abundant and reliable in the urban context, they are often scarce to non-existent in rural areas. The lack of connectivity coupled with remoteness, rugged terrain, and sparse and predominantly aging population [12] amplify the effect of emergencies in rural areas [4] and collectively constitute the rural EPR digital divide.

The rural EPR digital divide affects a significant portion of the country and hinders further gains in effectiveness in EPR observed in urban settings thanks to timely information exchange and connectivity. Ninety-seven percent (97%) of the U.S. territory is categorized as rural, housing 19.3% (60 million people) of the overall population [12], of whom 30% (15.2

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million) still lack mobile broadband access [9]. There is little expectation that these areas will be reached by commercial technologies in the foreseeable future, as mobile operators find it hard to justify the low return on investment of building infrastructure in areas with sparse and/or impoverished populations [13, 14].

In addition, rural first responders are inherently disadvantaged in terms of resources and training [5, 15] compared to their urban counterparts. For example, 95% of the fire force in rural U.S. is comprised of volunteer firefighters, whereas career firefighters comprise 70% of urban fire forces [16]. These technical, social and political challenges put in jeopardy (i) the health and effectiveness of first responders, (ii) the emergency preparedness, health and well-being of rural residents and (iii) the rural infrastructure and livelihood.

While technologically disadvantaged, rural communities have been shown to have a tradition of collective action [17] building strong relationships between agencies and community members, and taking charge of their own technological progress [13, 18]. These factors can be leveraged, to improve the resilience of rural communities to emergencies. A critical enabler of improved EPR in rural areas is timely information collection, integration and exchange.

Traditionally, low data rate, uni-directional technologies such as AM radio and SMS-based Amber Alerts have been utilized to disseminate EPR announcements. Such technologies, however, are not always appropriate for rural communities and are rapidly becoming obsolete, with the emerging information needs of EPR applications that require bi-directional exchange of large volumes of information across agencies [19] and between agencies and residents [20, 21]. As a result, modern EPR services mandate broadband wireless connectivity, leading to the establishment of a nation-wide first responder network FirstNet [22] by the National Telecommunications and Information Administration. FirstNet utilizes a slice of AT&T's network for prioritized public safety communications.

Two factors inherently bias its model against rural areas [15]: first, it assumes cellular network connectivity, which while reliable and abundant in urban areas is spotty or non-existent in rural areas [9]; second, the completion of this project requires private partnerships, as the $6.5 billion provided by the federal government will only cover a fraction of the projected $10-$15 billion cost [23]. As a result, the rural EPR digital divide will remain and further widen, as advanced communication technologies such as 5G become available in urban areas. In the face of slow rural penetration of commercial cellular operators, we envision that alternative technologies such as TV white space (TVWS) networks coupled with delay-tolerant point-to-point connectivity among community members can significantly improve EPR in rural settings by ensuring bi-directional exchange of rich information.

This paper proposes a comprehensive socio-technical framework and a multi-layer platform for information collection, integration, exchange and dissemination to community stakeholders including emergency agencies, first responders, local government and residents, enabling improved rural emergency preparedness and response. In pursuit of this goal we propose to consider important socio-technical components such as next-generation wireless networks, advanced data science, and user adoption and use models and theories.

The paper is organized in five sections, including the foregoing introduction. Section two describes the underlying premises of our integrative framework, including existing literature on mobile wireless networks, information sharing, data-driven capacity, and user adoption. Section three presents the framework and its main components as well as the interrelationships among them. Section four describes an illustrative example where the implementation of the framework may result in improved ERP. Finally, section five closes the paper by presenting potential implications of the framework and stressing its theoretical and practical contribution.

2 The Digital Divide in Rural Emergency Preparedness and Response: Identifying the Underlying Premises

In this section we briefly describe the underlying premises of our integrative framework: mobile wireless networks, information sharing, data-driven capacity and optimization, and adoption and use.

2.1 Mobile Wireless Networks as an Emergent Infrastructure

The lack of economic incentive for commercial broadband providers to deploy in rural areas has forced communities to take charge of their broadband connectivity. Thus, we have seen a plethora of technologies deployed through community initiatives, including cellular networks [13], TVWS [24, 25] and microwave/WiFi mesh [26–29]. This organic growth of community-owned and operated networks has increasingly been considered the most viable path forward to rural broadband [15]. While these technologies are currently exclusively-focused on providing single-network, stationary end-user connectivity, additional research is necessary to make them applicable for community services such as EPR. Such services will need seamless mobile connectivity with integration across networks and technologies. This raises challenges, in terms of network coexistence and client multihoming.

Wireless networks with infrastructure mobility have been considered at broad spatial scales. Several recent studies consider short-range infrastructure mobility with tight motion control for improved channel quality [30, 31]. Other works, such as Project Loon [32], drone mesh networks in the sky [33], and delay-tolerant networks [34, 35] design connectivity solutions for infrastructure-challenged areas, with some focusing particularly on disaster scenarios [35]. As with small-scale infrastructure mobility, all of these works, except [34, 35] assume that the mobility can be manipulated. Guo et Al. [34] present KioskNet, a delay tolerant network with mechanical backhaul realized through buses that connect Internet kiosks in rural India.

Prior research focuses on end user multihoming, however, multihomed mobile infrastructure has not been considered in the past. Multihoming solutions use both heterogeneous (e.g. cellular and Wi-Fi) [36, 37] and homogeneous technologies (e.g. WiFi-WiFi [38, 39] and Cellular-Cellular [41, 42]) and focus on transport protocol performance [43] and design [44–47]. All of these works, except [38] optimize the performance of a single end user. Work in cellular multihoming [45–47] tackles adaptive switching across collocated networks.

2.2 Information Sharing

Exchange of timely information by first responders and residents in emergency situations is a key determinant in of the effectiveness of the response [10, 48]. Enhancing preparedness during non-emergency periods via effective public information campaigns has been shown to also improve the effectiveness of response at a time of emergencies [49, 50]. These benefits hinge on the availability of broadband wireless connectivity [15, 24] and while advances in wireless networks for under-served areas [40, 51–60] bring promise for improved EPR, their incorporation requires critical technological and socio-political advances to make them practical for this application which is the focus of our framework.

Information integration and sharing involves four interrelated components: 1) trusted social networks 2) shared information 3) integrated data and 4) interoperable technical infrastructure [61]. On one hand, EPR requires effective and efficient collaboration among multiple organizations at different levels: individuals and neighborhood organizations, private and nonprofit sectors, and several levels of government [62–66]. We further postulate that in rural EPR, collaboration among heterogeneous actors is key for information collection and exchange, and thus for the decision-making capabilities of the key stakeholders [67–70]. On the other hand, integrated data and interoperable technical infrastructure facilitate diverse organizations (private, public, non-profit) to share information resources under the same standards and rules and in terms of common definitions and joint work processes and organizational structures [61, 71–75].

2.3 Data-driven Capacity and Optimization

The typical protocol designs for opportunistic (ad hoc) networks [76] seek to ensure point-to-point routing and communication [77–80]. In the EPR scenario, we are interested in timely exchange in two directions: (i) information collection originating from community members to a centralized repository, thus employing community members as a sensor network [81]; and (ii) dissemination from the repository back to community members in the presence of unreliable links [82]. The latency of both directions depend on the mobility patterns of nodes and in particular the frequency of access to a hotspot and the frequency of rendezvous [83].

Algorithmic network design and optimization consider link additions and node upgrades for delay minimization and/or structural measures optimization [84, 85]. We recently proposed node enhancement techniques suitable to social and transportation networks [86, 87]. Another set of relevant models relate to complex contagion on social networks [88–93], where uncertainty on links is due to decisions of nodes to forward as opposed to physical contact or connectivity, and the optimization problem of interest is influence maximization via incentives for nodes to propagate information [94]. The novelty in our envisioned models is the temporal and spatial importance of information dissemination necessitated by the seasonality of mobility patterns, and thus connectivity of community members

2.4 Adoption and Use

Models of technology adoption and diffusion comprise organizational concepts and social theories we employ in our framework. Existing models of diffusion and adoption highlight key factors for the innovation cycle of ICT with distinct phases: adoption (from initial knowledge to forming an attitude towards innovation), diffusion (communication of innovation within a social system), and upscaling (replication of pilots to a larger scale) [95–97].

An alternative model is the Technology Acceptance Model (TAM), introducing multiple factors that influence users' decision about how and when to use new technology: external variables, perceived usefulness, perceived ease of use, attitude toward using, and behavioral intention to use [98]. A recent model distinguishes between determinants and barriers for adoption categorized into outer (e.g. economic, political, social, demographic) and inner context (organizational, individual, and technological) factors [99]. It is necessary to consider previous models of technology adoption and use when applied to the rural setting and particularly the EPR domain, since they will help to explain to what extent the new technologies are being adopted by emergency managers, first responders, and the public.

3 Rural Emergency Management and the Digital Divide: Towards a Socio-Technical Framework

Emergencies are "events, observable in time and space, in which societies or their larger subunits (e.g., communities, regions) incur physical damages and losses and/or disruption of their routine function" [100]. Such events move through lifecycle phases: two pre-event (mitigation and preparedness) and two post-event (response and recovery) [101]. Throughout all phases, information serves a critical role in planning for and management of the emergency, but also for relationship building [102].

While our end-to-end socio-technical framework for rural information collection, integration, exchange and dissemination is useful in all phases, we argue that its impact will be highest during the preparedness, mitigation and response, as those phases rely on predictable user mobility and TVWS networks, which may all be disrupted during the relief efforts. An overview of our integrative framework is presented in Figure 1. The core challenge we set out to tackle is the limited connectivity in rural areas which in turn results in limited collection and exchange of timely emergency information for consumption by all community members.

We aim to understand and exploit the potential of opportunistic networks relying on regular user mobility and extending the functionality of TVWS networks by mobile clients which serve as data caches located close to first responders and affected citizens to facilitate data exchange. The framework is expected to allow the investigation of novel connectivity modes as well as the development of data driven models for detecting weak spots and evaluate appropriate optimization initiatives. It could also address adoption and use of the technology in improving ERP. For practical purposes, the framework can serve as a guide for emergency managers and policy makers in developing success strategies for propagating emergency information in rural areas with no or limited connectivity.

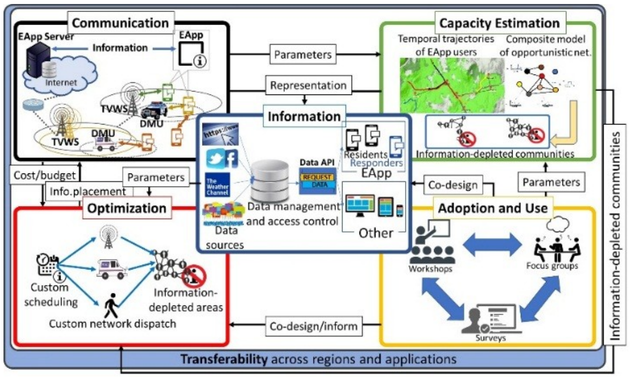

Figure 1: A Rural-Emergency Management Socio-Technical Framework

3.1 Communication: Wide-area Networks With Infrastructure Mobility

A key factor in the effective aggregation, presentation and exchange of EPR information is the ability for information sources and consumers to connect. The goal of this component is, thus, to develop robust models and protocols for wireless connectivity in support of rural emergency preparedness and response that leverage heterogeneous wide-area networks with infrastructure mobility. A key building block to our proposed wide-area network solution is the data mule unit (DMU), which is carried by the vehicles of various agencies (e.g. fire, EMS, post office and sheriff) and serves two primary purposes.

First, it provides constant Internet access to agency personnel (e.g. first responders) who travels in areas with TVWS backhaul and, second, it delivers delay tolerant access to EPR information to residents who lack reliable Internet access. The DMU architecture consists of a TVWS CPE, connected via Ethernet to a WiFi access point (AP). Using the CPE, our DMU connects to the wireless backhaul for Internet access, while simultaneously providing end-user access through WiFi. Futhermore, the DMU will have local caching capabilities that will store and forward and collect EPR information. This will allow residents to receive emergency preparedness information in a reliable way, although with some calculated delay.

3.2 Capacity and Optimization: Modeling and Reducing the Delay of Information Exchange

The dissemination of EPR information in areas without coverage can be improved by using community members and DMUs carried by utility vehicles. Therefore, our second component takes into account the capacity of an opportunistic pocket-switched network for exchanging EPR information over time. Knowledge about the community connectivity profile will result in the identification of sub-communities susceptible to "temporal information shortages". This profiling will also contribute to understand the disruptions in the network during the response and relief phases of an emergency event in comparison to normal situations (preparedness and mitigation).

Our framework measures capacity by means of an emergency smartphone app that supports the collection of information from different sources and its exchange among first responders, government agencies, and residents. We therefore assume that a community member within the range of a network will certainly exchange information through such app. The app collects individual mobility patterns, which may be affected by multiple factors (such as employment, friendship relationships, visits to local business, etc.) as well as Internet access (see Figure 2: on the left, there is a set of trajectories of community members and, on the right, there is an example of an opportunistic network among community members with connectivity profiles).

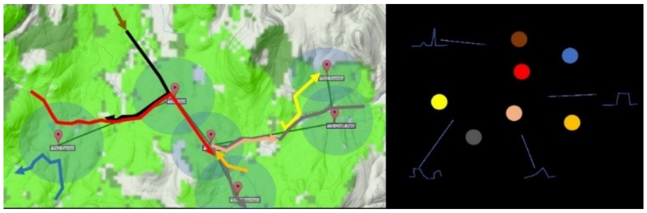

Figure 2: Modeling Information Exchange

3.3 Adoption and Use

The benefits of better connectivity in rural environments are the result of identifying and addressing the needs and expectations of the community. Therefore, technology adoption and acceptance by society becomes a key ingredient in the context of EPR. In addition, novel network architectures and optimization techniques have the potential for supporting information sharing, resource management, and collaboration among the actors involved in an emergency. However, this potential is only realized if the levels of adoption and use are good for all those actors, including first responders, emergency managers, and citizens. Thus, the adoption and use is the third component of our framework.

Adoption and use are assessed by conducting a needs assessment as well as several evaluations of adoption and use at different points in time. The goal of the needs assessment is twofold: on one hand, to analyze how the current situation may affect the success of a given project and how different stakeholders will embrace the new technology and data available; on the other, to explore the needs and expectations of the community in relation to the connectivity project and the optimization model. Among other, the needs assessment will focus on the main challenges of the project (and, therefore, the changes that need to be made, in addition to the introduction of new technology, for the benefits to be realized), the emergency information needs of the community, the current status with respect to available technologies and information uses, and the expected outcomes for first responders and for the public.

The different evaluations provide information about the progressive benefits of improving connectivity in a rural community regarding emergency management. The evaluations will therefore monitor adoption and use of the technology and related products (such as the app) and, in particular, they will look at the institutional (emergency management and other government agencies) and social (citizens) responses to improved connectivity and increased and better emergency information and the short-term results.

4 The Importance of Context: The Case of Emergency Management and the Need for Information Sharing in Thurman, Warren County, New York

Being a socio-technical framework, it is necessary to consider the social conditions around the potential technological solutions and artifacts. As explained early in this paper, EPR in remote rural areas have distinctive characteristics and particular challenges. The example of the town of Thurman, which shares the same key characteristics and faces some of the same challenges as other rural communities in the United States, attempts to highlight some of these particularities and briefly explain how they need to be considered in the proposed socio-technical framework.

With an average population density of 73 people per square mile, Warren County is a typical example of rural U.S. Several towns in the county, including Thurman, lack commercial mobile and broadband access. As of the census of 2000, there were 1,199 people, 466 households, and 338 families residing in Thurman. Thurman is therefore a typical example of a mountainous and remote town in rural US, for the town lies entirely inside the Adirondack Park, which makes physical and online communication difficult. In addition, given the physical characteristics of the area, natural disasters are likely to happen. In particular, there is high risk of fires, flood, severe storms, and ice jams, which could block rivers and divert their caudal elsewhere, resulting in damages to houses and public infrastructure.

Currently only 8% of the overall population are connected, yet EPR services heavily rely on constant Internet access. Because of the lack of commercial mobile and broadband access, the town recently secured a grant through NYS Broadband initiative which supported the deployment of a TVWS wireless network. The network is town-owned and operated, and currently connects thirty of the nearly three hundred households in Thurman. A hundred additional households fall in the current coverage area of the network. Therefore, there is potential for a wider use of this network to provide information to residents and first responders.

As in many other small jurisdictions, during the event of an emergency, several community partners are involved in its response. The Warren County Office of Emergency Services is usually the organization in charge of coordinating the efforts. However, the Warren County Emergency Medical Services, the Warren County Fire Department, and the Warren County Sheriff also play important roles during such events. In addition, other national organizations had also been present during these events. Thus, to optimize the response, it is key that all these organization exchange information among them as well as make sure that they make citizens aware of the situation and the way to proceed. In addition to the limited connectivity, some of these actors are geographically disperse and there is no easy way to communicate among them.

Given the features of Warren County and the recent emergencies the Town of Thurman has faced, we believe their situation is representative of rural area in the United States and, therefore, one that can benefit from the use of our socio-technical framework, both to better understand their particularities and develop solid potential technical solutions. We argue that rural communities like this one could benefit from the potential socio-technical solution presented in our proposed framework in order to better prepare for emergencies and face them when they happen.

5 Conclusions and Implications

Emergency situations, be they caused by natural hazards or by man-made situations, are usually characterized by threat, urgency and uncertainty. Therefore, in these situations, it is vital for citizens to obtain clear information on events and direction for action, as well as assurance of their safety. Communication between crisis response organizations and the public is, therefore, essential for coping with emergencies. First responders also need relevant information to assess the situation and take the right actions. In addition, the inability of first responders from many different agencies to communicate and share data greatly hampers the emergency response and may result in death or injury to themselves or those they strive to protect.

The topic of crisis communications among first responders and between them and the public has already been addressed by the literature, which shows that technical interoperability (that is, lack of compatible equipment) but also collaboration challenges (such as establishing and maintaining shared situation awareness and understanding organizations structures) hinder communication during emergencies. These are important challenges irrespective of infrastructure and geography.

However, in some rural areas, on top of the above challenges, emergency coordination and dissemination of information is also retrained by the lack of connectivity and a difficult terrain with mountains, valleys, and other physical obstacles that impede the use of more traditional ways to provide Internet access. Our framework tackles the difficulties of emergency management communication in rural settings by improving connectivity and optimizing the exchange of information and, therefore, by improving the flow of real-time information despite intermittent coverage. In addition, by focusing on adoption and use by the community, it considers the unique characteristics, needs, and limitations of rural areas. Our proposed socio-technical framework could be the basis for potential solutions to the problems mentioned before. Its consideration of social and technical aspects makes it not only potential more effective, but also more realistic and feasible.

Emergency preparedness and response are essential in securing the right to life with dignity and, therefore, in improving wellbeing and quality of life. Communities need to work closely with local authorities, public agencies, and relevant private sector organizations, in order to strengthen their own capacities to prepare for and manage the consequences of various potential disasters and other risks. Our framework would help to better understand the needs and develop critical technologies that will contribute to improving emergency preparedness and response in rural contexts. Some of the benefits of using the framework include, but are not limited, to better informed-decisions to prepare and respond to emergencies, potentially contributing to the social and economic revitalization of the rural communities and to increasing the quality of life of their residents.

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