Advances in Disaster Communications: Broadband Systems for First Responders

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1 Introduction

When a disaster occurs, first responders are dispatched to save lives, to protect property, and to assist in keeping order. To perform such duties, first responders require operational communications among themselves, coordination communications with other agencies, and communications with the general population.

In this article, I describe the evolution of public safety disaster communications since the initial use of radio about 90 years ago to the current implementation of dedicated broadband spectra for first responders. I discuss some of the challenges and opportunities that face public safety communication as it has changed from traditional voice radio to broadband systems using smart phones, tablets, and advanced devices. In particular, I outline the development of the First Responder Network, FirstNet, in the US which is a prospective solution to many of the communications challenges, especially during disasters, for first responders. I then analyze the prognosis for

FirstNet.

While wired communications, such as landline telephones, have been used since the latter half of the nineteenth century for disaster communications, the development of radio allowed untethered communications, thereby, removing geographical constraints on the responders. The use of radio, or wireless as it was then called, for police dispatch dates to the late 1920s when several radio enthusiasts in the Detroit Police Department installed a radio receiver in a police car. Such a one-way dispatch experiment continued for several years (ETHW (2015a)). In 1933, the Bayonne, New Jersey police began to use two-way radios to dispatch officers (ETHW (2015b)). In 1940, a major advance in communications came with the commissioning of a statewide two-way voice radio system for the Connecticut State Police (ETHW (2015c)). Until the past decade or so most public safety radio communication continued to be verbal and most communication needs could be satisfied by analog radio systems. The major constraint for such systems on public safety, nevertheless, was the blocking of the radio channel due to too many messages being transferred at a given time.

Rudimentary digital data transmission systems for public safety were introduced in the late 1970s (Corillo (2003)). However, the physical layer of these systems continued to be based on analog radio systems. Most police digital queries of that time period consisted of text-based requests, involving the determination of the validity of a license, or the issuance of a warrant, and, typically, were received via a single line display in the police cruiser.

Over the years, the complexity and scope of incidents requiring first responder response have increased, with 9/11 being a prime example (Simon and Teperman (2001)). No longer is just a single police or fire department called to respond to a disaster, but, often-times, a multiplicity of agencies with common purposes, are needed. In addition, the definition of first responder has been expanded from just local law enforcement and fire personnel to include those whose missions might include monitoring the environment, protection from biological and chemical hazards, and restoration of basic services. Each of these groups has specific communications requirements for their internal operations, as well as a need to communicate and share information with other responding agencies and stakeholders.

Another major change in communication resource needs for first responders is based upon the now universal use of smartphones, tablets, and other devices that connect to the internet. Many applications that first responders utilize, such as mapping, hazardous material identification and detection, local weather forecasts, etc., are not housed in a single device, or even a specific network, but are dependent on data available via the cloud. This sharing of data yields insights on the severity of the incident not only to the Incident Commander on the scene, but to all responders and their supervisors (Karagiannis and Synolakis (2016)). In the past decade the need for internet connectivity at an incident has moved from (a) not needed since we have proprietary systems that give us all the information, through (b) possibly useful, but not required, to (c) now, absolutely necessary for an incident to be efficiently managed.

Parallel to the growth and evolution of communication needs of first responders in a disaster are the communication demands of the news media and the communication needs of the humanitarian responders, who are involved in essential activities such as arranging for meals, shelter, and medical services for the displaced/victimized population. Furthermore, notifications of family and friends as to the welfare of survivors and possible reunification also require communications. While in earlier times such communications took place on separate radio channels and were delayed in time because of the limitations of existing technologies, currently, many, if not most, of these activities occur simultaneously to disaster response communications. Thus, with exploding demand from different stakeholders, there is a critical need for enhanced communication resources immediately post the disaster and as the recovery and reconstruction take place.

The communication bandwidth requirements post-disaster are schematically illustrated in Figure 1. As shown in the figure, the communications bandwidth requirements during a disaster increase rapidly during the first 24 hours, leveling and peaking during the first 3 days, and decreasing during the next 30+ days. This assumes, however, that it will be possible to restore much of the infrastructure during this period. For some emergencies and disasters this is, indeed, possible. However, catastrophic disasters such as Hurricane Maria, which struck Puerto Rico and other Caribbean islands in September 2017, have become extended disasters where the realities of the first 3 days in terms of infrastructure losses following the disaster have been extended into the first 6 months (FEMA (2017)).

It is important to note that wireless access to the internet for smart devices used by public safety personnel and first responders does not occur via dedicated public safety networks. Rather, it is provided by commercial wireless carriers such as Verizon, AT&T, T-Mobile, etc. Each carrier supplies broadband service based upon current broadband standards that can be accessed by devices whose owners have direct contracts with the cellular provider. Additionally, most carriers have roaming agreements that allow devices to shift to another carrier's network if there is no network availability from a device's contracted carrier.

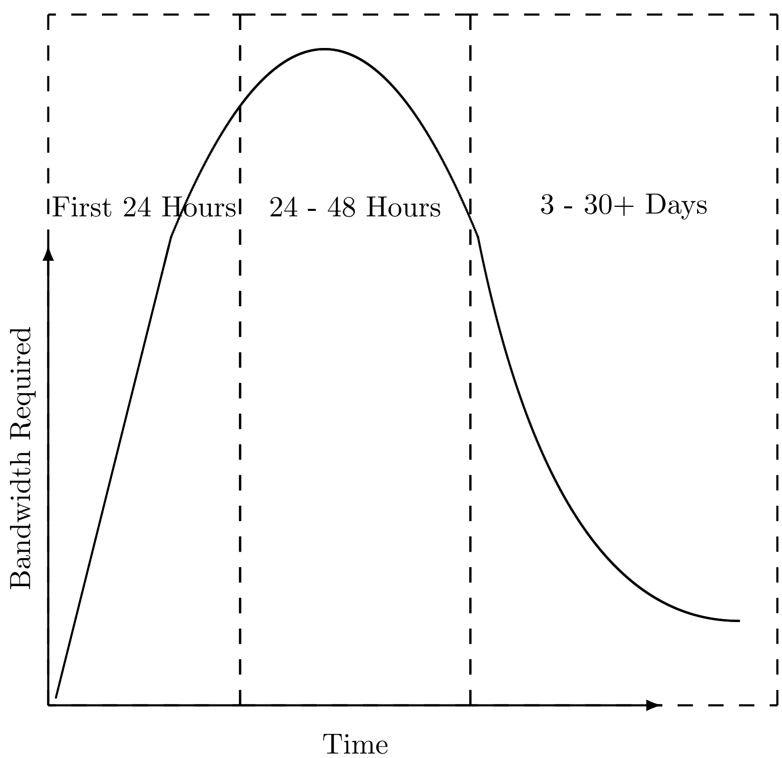

Figure 1: Post-Disaster Communications Bandwidth Requirements

Hence, the broadband wireless spectrum, shared among first responders, the media, humanitarian agencies, and the general public, is a scarce resource today with growing competition and increasing demands among users for the available bandwidth. For example, in the early tests of using commercial broadband for public safety at major events such as the Rose Parade in California on New Year's Day, it was noted that, when a parade float passed, many of the parade viewers would send their photos and videos of it; thereby, significantly degrading network performance (Bishop (2017)). Currently, there is a non-preemption status for any wireless user; consequently, a first responder needing to access building plans from the internet is competing with users sending low-priority messages. First responder communications are put in a queue with other users making it difficult for them to perform their functions efficiently and effectively.

1.1 Needs of First Responders

In 2015, Motorola surveyed public safety officials to determine their most pressing problems (Motorola (2015)). The major pressing problems were found to be:

- An increased level of community engagement needed;
- Real-time data should be accessible in the field;
- Increased communications with neighboring agencies are essential;
- Collaborative technologies must be used to expand capabilities;
- The technology skills of first responders must be better managed.

The solution to each of these pressing problems would likely require use of a broadband wireless service with broadband providing the high data rate needed and wireless allowing the users to be physically untethered from a network. For example, currently, police and fire departments can no longer just respond to calls and allow the news media to listen to their dispatch radios and view their call logs to determine which incidents are newsworthy and which of these rise to the importance of immediate reporting. Public safety agencies now routinely engage the community through the use of social media, including Twitter and Facebook, as the incident unfolds, to alert and inform the public and, in many cases, seek the public's help.

Moreover, as any incident unfolds the first responders need to access data. For example, in the case of a tank truck accident, the first responding unit on the scene can use broadband to instantaneously determine whether the incident is likely to escalate by determining the tank's contents through a search of the database of tank placards. An accident involving a truck that is leaking an inert, nontoxic gas, such as argon, has very low probability of impacting just beyond the accident site and, similarly, has a low probability of harm to first responders who take standard precautions. However, a truck leaking a chemical that generates toxic, explosive vapors must be managed significantly differently to prevent additional injury to the population and to the first responders themselves.

Keeping neighboring agencies informed of incidents and coordinating responses near their jurisdictional borders are other important tasks. Some incidents might require the immediate response from a neighboring agency based upon an mutual-aid agreement. Other incidents might be better managed through assistance in another jurisdiction. For example, a traffic jam due to a road closure near the incident could be minimized if motorists were encouraged in advance to take an alternate route. This could be very helpful in the case of evacuation networks (see, e.g., Vogiatzis and Pardalos (2016)).

Furthermore, the work of first responders has expanded to include many functions that were not even considered their responsibility only a few years ago. However, many of these functions are only infrequently performed and often require specialized skills and equipment. Collaboration, via the internet, can enhance every agency's capabilities and increase the availability of services and the efficient management of incidents.

The last pressing problem from the Motorola survey addresses the skills gap. The training requirements of first responders have grown exponentially. Recurrent training and certification on new techniques, equipment, and types of incidents have become mandatory. Enhancing and keeping current the appropriate skills for first responders are important concerns not only to their agencies, but to all.

1.2 Types of Disaster-Related Communications

The communications needs of first responders can, generally, be divided into two main categories: Mission Critical and Non-Mission Critical.

Mission Critical Communications are classified as those that have the highest urgency and need the maximum reliability (Motorola (2013)). Mission critical voice and data messages must be transmitted immediately with the lowest possible latency (delay). Currently, almost all mission critical communications among first responders are transmitted over channels dedicated to the primary agency. Police and fire dispatch are prime examples of mission critical communications. For situational awareness (cf. Karaggianis and Synolakis (2016)), most mission critical communications are not single user to single user, but must be received simultaneously by all involved. Conventional push-to-talk radio, with each radio receiving all transmissions, is the most used technology for mission critical communications. The key metric that defines the performance of mission critical communications is reliability. Many first responders believe that simpler is better for mission critical communications.

Non-Mission Critical Communication includes an extensive class of messages that does not have to be transmitted with the highest urgency, but can be relegated to a lower priority. In a disaster, these non-life threatening or non-safety-of-life communications are important, but not so important that they must be transmitted with minimal latency. Messages, such as those involving logistics, slowly changing data, etc., are also included in this category. They are often from one individual to another without the broadcast requirement needed for situational awareness. While in many cases, non-mission critical communications are transmitted over the same communications channels as mission critical communications, they may also be transmitted over a secondary channel or by an entirely different mode such as cellphone, text message, or email. This is important in the case of the transmission of sensitive information, such as the names, personal information and/or relevant medical information.

This paper is organized as follows. Section 2 of this paper briefly reviews communications technology. Section 3 discusses interoperability and broadband. Section 4 traces the history of the First Responders Network, FirstNet. Section 5 discusses complementary technologies that should be used in conjunction with FirstNet. Section 6 describes the advanced features needed in Long-Term Evolution (LTE) systems for first responders. Section 7 presents the efforts in other countries for broadband for first responders. In the concluding Section 8, open research questions regarding broadband for first responders are summarized.

2 Brief Background on Communications Technology

This section briefly reviews Land Mobile Radio (LMR) and LTE broadband networks.

2.1 Land Mobile Radio - LMR

Land Mobile Radio is also known as conventional 2-way radio communications that is ubiquitous in public safety agencies. The radios in police cruisers and fire trucks and the handheld radios that are strapped to the belts of our first responders are the prime examples of LMR. Almost all LMR systems are controlled directly by the using agency but there is often no interoperability among systems. Within the US, most first responder dispatch uses legacy LMR systems. Despite new technology and frequency bands becoming available, agencies often stick with LMR systems defined decades ago because they are mission critical and work. Many agencies do not replace their legacy LMR dispatch systems due to financial constraints. The legacy behavior limits interoperation, since, often, interoperation cannot occur by just changing the channel on a radio, but requires a whole different radio, antenna, and protocol. (Noll (1985), Orr (1981))

The simplest form of LMR, known as simplex, uses a single frequency, f_1, and is illustrated schematically on the left-hand side of Figure 2. Simplex radio's transmissions can be received by all other radios in the system simultaneously, similar to a party line phone. The two key limitations of simplex LMR are the power level of the radios, which often limits battery life, and the line-of-sight nature of radio propagation which introduces shadowing effects. Both of these couple to reduce the range of the transmissions. Simplex LMR systems, however, have the highest reliability, since no additional infrastructure, other than the radios and their associated antennas, are necessary for communications and user to user relay is possible. That is, if responder A cannot directly communicate with responder C, but responder B can communicate with both, responder B can serve as a relay between A and C (Noll (1985), Orr (1981)).

To extend the range of LMR systems and increase the spatial coverage, a repeater can be installed. A repeater is a receiver/transmitter pair. Users transmit to the repeater on one frequency, f_1. The repeater simultaneously retransmits (or repeats) the transmission on another frequency, f_2. The users' receivers are tuned to this frequency, f_2, and receive the transmission (see Figure 2). In this way, the limitations that can be attributed to lower transmitter power and shadowing are diminished. The repeater, which is often located at a remote location such as the top of a nearby mountain or tall building, must be operational for the system to work. Repeater sites almost always have redundant backup power systems so that the repeater continues operating even when primary electrical power is interrupted. At times, a hot-standby repeater is used to ensure service when the primary one

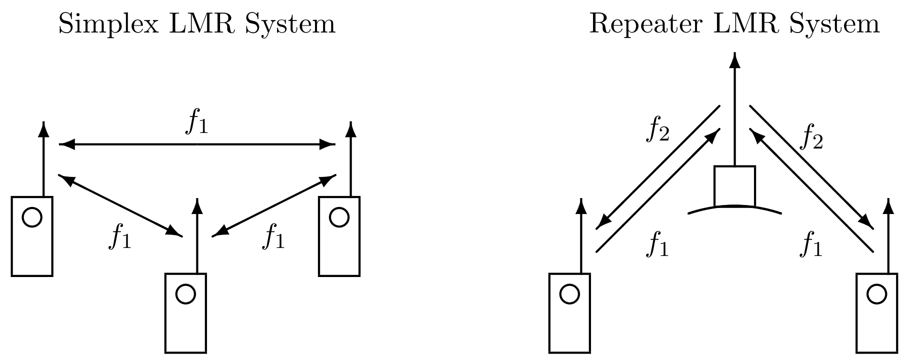

Figure 2: Simplex and Repeater LMR Systems

becomes inoperable. Some systems include an additional standby repeater at another location to ensure highest reliability. Proper system design will often include an option for operation without the repeater for cases when the repeater is inoperative or units are out of range of the repeater.

One key limitation of conventional LMR is that the radio spectrum is a scarce resource. Conventional LMR requires a dedicated channel for each agency. Repeaterized systems require two channels per system. Radio channels may be reused with a spatial separation that is often measured in hundreds of miles. In addition, adjacent or even nearby channels may not be used in a close geographic area. One way to alleviate the spectrum shortage is *trunking*. A trunked system is based upon the premises that (1) each user agency normally uses only a relatively small amount of the channel capacity and (2) that the usage patterns of the users do not have significant overlap or are primarily just certain times of a day. Trunked systems allow multiple users to share a group of channels. While at times there might be a slight delay for a channel to become clear, the latency is not always noticed by the user. Although the trunking controller and repeater must be in operation for the system to work, with proper design, the system can continue to be operational if the controller/repeater is out of service.

While the association of LMR with a first responder's handheld radio implies that the system is analog, three digital protocols for LMR communication have been developed over the past two decades. In addition to transmitting voice, each can be configured to include short text messages (SMS) service and limited interoperability. Some even have the possibility of quasi-private user to user communication. These digital protocols include:

1. Terrestrial Trunked Radio (TETRA) is a European standard designed for public safety networks. For technical reasons, it does not meet the FCC-mandated spectral mask for use in public safety networks in the US, although several demonstration projects have been implemented. It is also extensively used for transportation networks in the US and worldwide and the military (ETSI (2018)).
2. Project 25 (P25), also known as APCO-25, is a North American standard for digital radio communications for use by public safety organizations to enable interoperation. This standard is developed and promoted by the Association of Public-Safety Communications Officials, APCO. The standard is open so that any manufacturer can develop radios that conform to the standard (Project25 Interest Group (2018)).
3. Digital Mobile Radio (DMR) is an open digital mobile radio standard defined by the European Telecommunications Standards Institute, ETSI, in 2005 and used internationally (ETSI (2013). It was developed in tiers, the first for simple low-power, low-cost handheld radios in Europe. It has been extended to include talkgroups where groups of users can have partyline-like communications.

2.2 Long Term Evolution - LTE

As cellular telephones became more popular and advancements were added so that users could send text messages, email, and access data services, the standards have evolved from the original analog cell standard, AMPS, through multiple generations. LTE was defined in the third generation standard to increase the data speed and to harmonize various data standards. Most wireless carriers now use LTE technology, including Verizon, which had previously used an incompatible standard. As in all cellular systems, the users' devices connect to cellsites (often known as towers). From these sites, the traffic is transmitted over the backhaul to the central office, known in LTE as the Evolved Packer Core (EPC). The EPC is an Internet Protocol (IP) based network that routes data among cellsites and connects devices to the internet. A key feature that led to the implementation of LTE networks is that each LTE cell can support approximately four times the data capacity when compared to previous generation of wireless networks. (Signals Research Group (2014))

Currently, LTE networks are clearly well-established in all markets. The needs of first responders require some extensions to LTE. These extensions are discussed in Section 7.

2.3 LMR vs LTE

To summarize the differences between LMR and LTE, an LMR system uses preconfigured channels. Overlapping LMR coverage is provided by using different frequencies. The bandwidth and throughput of an LMR system are determined at the system design time. Users using their own LMR channel do not impact users of other LMR systems. In contrast, in the case of LTE, all sites operate on the same frequency; thus, the system must be designed and tuned to minimize overlapping coverage and the *channels* are dynamically managed at each site. The bandwidth and throughput are determined by need and availability to minimize congestion. One can envision an LTE system as one large data pipe containing individual data pipes. Near the site all pipes may be used together and the capacity is 74 Mbps. As a user moves away from the celltower, the capacity is reduced; however, the system can handle different communication demands.

3 Interoperability and Broadband

The 2015 Motorola Survey concluded that 78% of those surveyed desired easy interoperability with neighboring agencies and 73% desired the ability to connect different devices and networks together. This issue of interoperability was identified decades earlier by communications professionals. It was not until the well-publicized communications deficiencies during the World Trade Center attack on September 11, 2001, that interoperability issues became apparent to decision-makers and those responsible for allocating sufficient funding to mitigate the problem (Simon and Teperman (2001)). Almost simultaneous to the identification of the deficiencies of the traditional radio LMR systems, advanced devices such as smartphones and devices were thought to become a panacea. First responders embraced broadband using commercial technology and wireless networks. The growth and easy use of LTE networks for mobile broadband access became a natural for use by first responders. While LTE networks provide reliable, and now ubiquitous access, there are several drawbacks that prove difficult for first responder use.

Because the commercial carriers' business model is to satisfy as many users as possible, a goal of a wireless provider is to allow every user some access to the network. The primary drawbacks that this universal access causes include prioritization and data throttling. Despite the wireless providers' claims of unlimited data and equal priority in their advertising, the wireless bandwidth is still a limited resource. Most of the time, users do not realize this. If too many users are attempting to access the broadband network, some users' data transfer speed is throttled back. This choice is often made by the provider based upon a user's total data usage over a period of time. In addition, if a user uses above a certain threshold of data and the network is congested, the provider prioritizes other users whose usage has been less. To the first responder community, this is a major limitation, since, first, during an emergency incident, the network will become congested with users and the data needs of first responders will likely exceed the throttling limit.

In short, when a disaster occurs, broadband use (smartphone/tablet) increases to the point that the network becomes congested and throughput essentially goes to zero. First responders who have immediate need for the broadband network cannot access the network.

3.1 What is Needed for Public Safety Broadband

After careful study, it was concluded that the broadband network needs of the first responders could be summarized as follows:

- Public safety broadband should use 700 MHz LTE to allow use of Commercial of the Shelf (COTS) devices;
- The network should be fully interoperable on a nationwide basis;
- Bandwidth will not be an issue for normal operation;
- While bandwidth becomes an issue when a large incident occurs, most incidents occur in a relatively confined geographically area involving only a small number of cell sectors. The network congestion is likely to occur in a limited region;
- Real-time network management will be required so that public safety will have pre-emptive priority.

First responders have tremendous communications challenges. Currently, in the US, there are over 10,000 radio networks dedicated to first responders (in the broadest sense). There are 3,100 counties and over 70,000 public service agencies in the US. In addition, there are over 550 recognized Native American tribes that perform their own public safety activities. A very rough estimate from these numbers indicates that there could be several hundred thousand devices used by first responders connected via the wireless network.

To satisfy these requirements, a national broadband network, operating in the 700 MHz LTE band was envisioned. The network could be built by a public-private partnership. While seed money from the government would be required, the network itself would be self-funding through network fees with the seed funding eventually returned to the government (NTIA (2012), Farrill (2012)).

4 History of FirstNet - First Responder Network Authority

To build, deploy, and operate a Nationwide Public Safety Broadband Network (NPSBN) based on a single, national network architecture, an independent federal authority with a statutory duty and responsibility to take all actions necessary was created as Section 6204 of the Middle Class Tax Relief and Job Creation Act of 2012, PL 112-96, approved February 22, 2012 (PL 122-96(2012)) . The authority, named *First Responder Network Authority (FirstNet)*, was given the statutory responsibility to establish a national public safety broadband network, which includes not only the Core Network, but also the Radio Access Network (RAN) in each state or territory. For the purposes of the act there are 50 states and 6 territories, the District of Columbia, Puerto Rico, the US Virgin Islands, Guam, Micronesia, and Tribal Lands.

The statute also specifies that FirstNet create a Board of Directors with 15 members and establish advisory councils. It also requires that each governor of each state will appoint a Single Point of Contact to interface the state/territory with FirstNet. In addition, the statute created a technical implementation board to define the network. Band 14, a 20 MHz of spectrum dedicated nationwide for public safety in the 700 MHz LTE frequency range, was specified for the network with the law requiring the issuance of one nationwide license to FirstNet. The statute also specifies a 25 year life for FirstNet. The final network specifications included the use of 3GPP Standard Band 14 LTE with a 10 MHz wide uplink and a 10 MHz wide downlink. These frequencies had already been allocated for public safety use on a nationwide basis, but no licenses had been issued. To achieve higher reliability, a higher transmitter output power would be allowed for these Band14 devices, than is allowed for conventional smart devices.

The network will consist of the Radio Access Network (RAN), which is the collection of cellsites that the users access and the Extended Packet Core (EPC), the back office of the network. The system architecture of

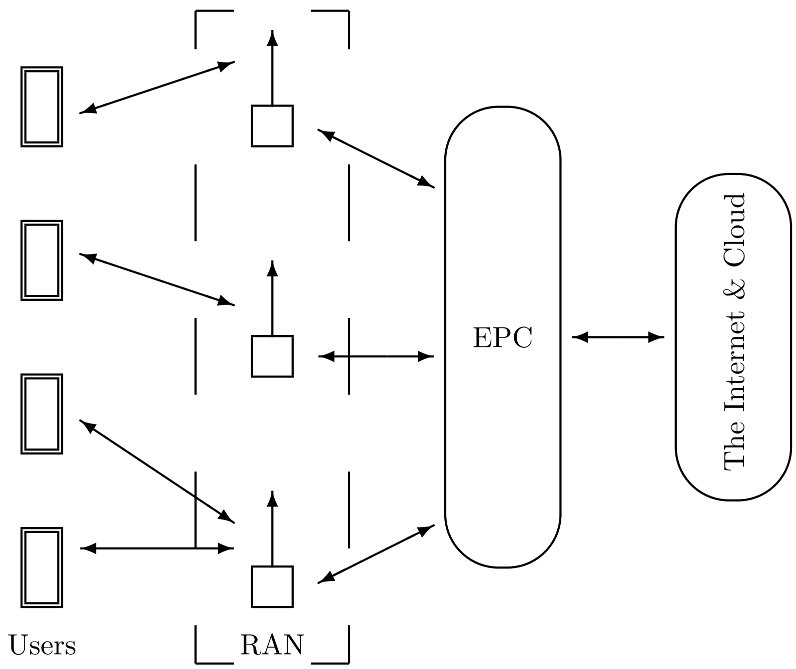

Figure 3: FirstNet System Architecture

FirstNet is illustrated in Figure 3. While both will be built by FirstNet, the possibility that states could opt-out of the FirstNet RAN and build their own was considered and will be discussed in Section 4.2.

4.1 Public-Private Partnership

The actual design, construction, and operational management would be delegated to a public-private partnership. The seed money, raised from spectrum auctions, would be used for the initial construction of the network. User fees on devices utilized by first responders and/or public safety on the network would pay for the operational expenses. In addition, during non-disaster situations, the partnership would be allowed to re-sell the network capacity to other users. At a value of $46.5 Billion, FirstNet is one of the largest public-private partnerships (Ross (2017)).

The contract was awarded on March 31, 2017 to an AT& T-led team that includes Motorola, General Dynamics, Inmarsat, and Sapient. Each of the partners has specific expertise it will bring to the project. Because AT& T currently manages a nationwide LTE system, the selection team concluded that they possess the necessary organizational and managerial skills for FirstNet to succeed. FirstNet will provide the 20 MHz of Band 14 spectrum and $6.5 billion in initial funding to the partnership. For a 25 year term, the AT&T-led consortium will deploy and operate the NSBN. During this time, AT&T is expected to spend about $40 billion for construction, operation, and maintenance of the network. The consortium will also ensure that the network evolves with the needs of first responders and with advances in technology.

When FirstNet's spectrum is not being used by public safety, AT&T may resell the network for other commercial purposes. First responders will be prioritized over any other commercial users on the Network. The contract will be overseen by the FirstNet Network Authority to ensure that the partners deliver innovation, appropriate technology, and customer care (FirstNet (2017)).

4.2 Opt-Out Provision of FirstNet

Probably the most controversial part of FirstNet was the opt-out provision. While the core network will be built by the FirstNet Partnership, states and territories would have the option to build their own Radio Access Networks (RAN), i.e., the cellsites and the associated backhaul. States who would opt-out of FirstNet would be required to construct their own Radio Access Network that would interface with the FirstNet core network and provide at least as good coverage as the consortium-built RAN would. As part of the FirstNet proof of concept, there were several demonstration networks, both temporary and quasipermanent, constructed to demonstrate FirstNet and validate it's features. These would also be integrated into the final network.

The opt-out decisions quickly became contentious, since many states, at first, were not convinced that FirstNet was providing them enough information to make an informed decision. In addition, due to the differing of freedom-of-information and state government contract laws and regulations, some states did not believe that they could properly evaluate FristNet's state plan for that state. While the statute prescribed funding for RAN construction and provisions for those states to license and control the FirstNet spectrum in their states, many states did not believe that the funding and restrictions were transparently outlined to them. Separately, it was also felt that the AT&T led partnership was playing hardball with states considering opting out. For example, AT&T offered states opting-in the ability to purchase devices that would connect with the current AT&T LTE network. AT&T would modify its current network to allow these public safety devices to preempt non-public safety users during an emergency (Engebretson (2017), Wendelken (2017a)).

While a number of states considered opting-out, often hiring consultants to develop specifications for the alternate RAN that would be constructed at no cost to the state, by December 28, 2017, the final deadline to opt-out, all 50 states, the District of Columbia, Puerto Rico, the Virgin Islands, and several Pacific Territories opted-in (FirstNet (2017c)). New Hampshire was the only state that formally opted-out of the FirstNet RAN. However, when it became apparent that it would be the only state/territory that would opt-out, New Hampshire reversed its course and opted-in to a FirstNet constructed RAN (Sununu (2017), FirstNet (2017b)).

4.3 FirstNet Public Safety Users Quality of Service and Preemption (QPP)

In implementing FirstNet, the AT&T-led consortium divided public safety users into two tiers, primary and primary extended. Each tier will have different priority and preemption status. The monthly user fee for a device will depend on its tier; the primary extended tier device will have a lower monthly cost.

To speedup the implementation of FirstNet, because AT&T is a nationwide wireless carrier, the FirstNet consortium has immediately implemented first responder pre-emption on its current network. AT&T has indicated that FirstNet will be multiband and it will provide public safety with priority on all bands of its network, not just band 14 (AT&T (2017)).

Primary users will include firefighters, police officers, and EMS. They will be the only network users who can actually pre-empt another user on the network. Primary public safety users will have a special access class. Users in this class will be exempt from throttling and barring. In addition, users in this class will have a high-priority access flag that will give them priority treatment during the various call setup stages. In times of high Band 14 traffic loads, non-primary public service users will be offloaded to other LTE bands (Ramey (2017)).

Primary extended users will not have the preemption capabilities that primary users have; rather, they will still have priority status on the network.

Special incident management level priority will exist to allow any specific user to be lifted above other traffic for a specific period of time through a manual form of priority that users can provision through an incident management portal. Thus, should a primary extended user (or even just a normal user) be the first unit on the scene of an incident, that unit can assume the same properties as a primary user. It is expected that many agencies will have a much larger number of primary extended users because the price for these users will be less than the price for primary users.

5 Complementary Technologies

It is important to understand that FirstNet does not live in a bubble and there are complementary technologies that should be used to supplement first responders' needs. FirstNet is expected to last over two decades; thus, it is clear that the FirstNet of 2037 will probably look significantly different from the FirstNet of 2017.

5.1 ATSC 3.0

While FirstNet is designed for use by first responders, getting information to the affected population is also of major importance to first responders. For example, informing areas to evacuate and suggesting routes to take are important not only to the first responders, but also to the general public. Despite the social media efforts that first responders are currently ramping up, broadcast TV and radio can still play an important role in informing the public. Also, new TV standards include selective information transfer that can be used to complement FirstNet.

Our current broadcast emergency alert system in the US was developed during the Cold War to allow the President to address the country in times of emergency. It is based upon over-the-air broadcast technology which assumes that most of the population will have access to broadcast TV and radio. A key difference between broadcast and FirstNet type communications is that broadcast is a one-to-many communication without any response or acknowledgment. Even when IP type communication is used, there is some acknowledgment that the message is received, even if not acted upon. Because of the lack of acknowledgment or retransmission, broadcasting is inherently exempt from the congestion issues facing LTE networks. There is only one transmitting user on each channel who controls all material distributed. Under current broadcast technology, broadcasters can only send a single stream to all viewers, that is, all recipients of a broadcast station receive the same broadcast.

Broadcast transmissions are also highly reliable, since the transmitter site is designed for robustness and redundancy. All transmitter sites have an emergency source of power. There are usually multiple ways the studio can connect with the site. There is often a backup transmitter and antenna which allow the station to stay on the air throughout almost any disaster.

A next generation TV standard, ATSC 3.0, is currently being completed (Chernock et al. (2017)). It expands the definition of television broadcasting to include not only traditional over-the-air television, but to include seamless integration of mobile devices. One key element of the standard is the ability to deliver multiple data streams that are tailored to specific segments. For example, multiple language support is one. The ability to combine an over-the-air stream to an internet distributed stream is another to achieve enhanced capability of the user experience is another. Each stream can use its own coding and modulation scheme therefore allowing almost unlimited options.

Part of this standard is an Advanced Emergency Alert (AEA) feature. This improves on the current emergency alert crawler, which is often seen on TV, but is often ignored since the alert is too general. ATSC 3.0 is designed to provide direct interaction between the TV broadcaster and the TV receiver. There will be a series of prompts and summaries on each device that will identify items of interest to that viewer. The user may select what alerts he/she will want. Rather than just the slow crawler at the bottom of the screen as currently done, there will be the ability to transmit graphics, multimedia, etc. Alerts can also be geotargeted to reach their primary audience in a given geographic area. Another feature is that devices can be woken up by an AEA alert, thus alerting those who do not even have their devices on. In a sense, this turns the device, TV, smartphone, tablet, etc., into the equivalent of an emergency pager.

It is expected that, when fully implemented, ATSC 3.0 will provide broadcasters with a more robust and reliable public warning and safety information communications system and leverage broadcaster's major role as public information provider during emergencies.

These multiple streams, the ability to target a stream to a small number of or even just a single user, and the ability to wake up devices will also allow the secure transmission of information and data to first responders. For example, a map or document might be sent over the broadcast channel to first responders without taking up the bandwidth of the LTE network. Because ATSC 3.0 works in the broadcast mode, users many modify their streams at any time (Siegler (2017)).

It is important to realize that ATSC 3.0 technology is complementary and can be used collaboratively. Broadcasted data and video traffic, offloaded from the LTE system, during times of emergency will enable the LTE to do what it does best, mission critical communications (Chernock (2017)).

5.2 Dedicated First Responder Wi-Fi

Despite all the promises for bandwidth availability from FirstNet, it is anticipated that first responders demands for bandwidth will soon exceed the supply. There are some applications whose communications needs can be better satisfied by other methods than an LTE network. For example, video surveillance is very bandwidth intensive and generates multimegabit-per-second data streams. The backhaul from fixed cameras can easily be fulfilled by a licensed microwave Wi-Fi system operating in the 4.9 GHz band licensed for public safety. It will provide a high capacity network with low latency, ideal for such operations. Properly designed the Wi-Fi nodes can become a redundant mesh network. (Lambert (2017)).

For temporary surveillance and extending radio coverage, a tethered drone could be used. Again, the 4.9 GHz band could be used to both to convey video from the drone and link it to the ground-based mesh network. This is important when the incident is out of range of many of the communications resources. Having both a radio range extender and video will enhance the capabilities of first responders (Gilbreth (2017)).

5.3 T-Band and 700 MHz LMR

Despite all the communications advantages and new opportunities that FirstNet provides first responders, there still will be a need for mission critical voice communications separate from FirstNet for the forseeable future. In the creation of FirstNet, the statute required that the T-band, the radio spectrum between 470 and 512 MHz, be auctioned off, most likely for TV stations. The T-band is used for public safety communications in eleven major metropolitan areas and was originally used by TV channels 16-20. As spectrum congestion increased in other frequency bands in these areas, the T-band was allocated for public safety. However, by 2023, all users of the T-band will be required to relinquish their use of the band. The funds to replace the current T-band systems will be generated by the T-band spectrum auction so that there would be minimal financial impact on the current users or the government with this reallocation (FCC (2016)).

Clearly, the same pressures on the radio spectrum that led to the creation of the T-band are still faced by public safety agencies using T-band. The 700 MHz spectrum allocation for FirstNet includes some limited contiguous spectrum for LMR use by first responders. However, these frequencies cannot be used as direct replacements for T-band frequencies since equipment, propagation coverage, location of repeater sites, etc., are required to be different. Thus, the 700 MHz frequencies are not a direct replacement (Springer (2017)).

In the distant future, as Mission Critical Push-to-talk Voice-over-LTE and other extensions are created to enhance the LTE standard, it might be possible to reduce the reliance on LMR technology as it presently exists. However, until this happens, public safety agencies will continue to use LMR for much of their mission critical operations.

6 International First Responder Networks

Broadband for first responders is not just an issue in the US, but it is a worldwide issue. The problem becomes more pressing in many less developed countries when they host a major international event such as the Olympics. For an overall view of LTE networks for public safety worldwide, see Lynch (2014) and Kable (2016).

Brazil, as the host for the 2014 World Cup and 2016 Olympics, provided an ideal demonstration site for LTE technologies and public safety. The Brazilian Army extended its LTE trial in 2014 in Rio de Janerio (Wendelken (2014)). Additional demonstration LTE networks in major Brazilian cities were described in Tetra Today (2016). The Brazilian system was the first major event with broadband LTE. About 70% of the users were 4G (Prescott (2016)).

England was one of the first countries to achieve interoperable voice communications between all emergency service users through a single system, Airwave. Developed in 2000, the Airwave network is a public-private partnership. Currently, England is now the first country to fully replace its singular nationwide public safety network (Kable 2016)). It is expected that the network will be operational by 2020 (Jackson (2017)).

South Korea, the host of the 2018 Winter Olympics will begin nationwide deployment of its public-safety Long Term Evolution (LTE) network with projects including one for the Olympics. The country will be investing about US$880 million to deploy the network and US$900 million for 10 years of operation following pilot projects in 2015 and 2016. Much of the nationwide network will be completed by 2020 (Wendelken (2017b)).

Canada, because of its long common border and need for interoperability with the US will build a Band 14 LTE network that is similar to FirstNet. One question that has been raised in Canada is that, due to security concerns, equipment by several vendors has been forbidden to be used on the US FirstNet. This raises some questions on how interoperability will occur

DRDC (2017).

Other countries including Australia, Hong Kong, China, Chile, Finland, and France are in the planning, pilot, or early operational stage of first responder broadband.

7 Features Needed for LTE Networks to be More Functional for Mission Critical Communications

Although an LTE-based FirstNet will be a boom for public safety, there are several enhancements or extensions to the LTE standard that would make an LTE network even more useful and that would remove some of the limitations of the LTE network. These are needed especially when mission critical communications will be transmitted over the LTE network and reliability will be paramount.

The first needed enhancement is *Proximity Services*. Smart devices using LTE require a cellsite to communicate with each other even if the devices are in close proximity. Without an active cellsite two LTE devices cannot communicate with each other. Proximity services will allow devices on the network to identify other devices in close physical proximity and enable them to make device-to-device communications even when the LTE network is not functional or both devices are out of range of a cellsite (Bishop (2017b)).

Because first responders might use their devices in locations that are not in line of sight with the cell towers, a second enhancement, *User Equipment to Network Relay*, must be implemented. This feature will allow a mobile device to serve as a relay for other devices to the nearest cellsite and, thus, provide connectivity for these out of range devices. In addition, this feature allows mobiles to act as relay points between other mobiles, permitting communication without going via the network even if the mobiles are out of direct range (Bishop (2017b)).

The full convergence of a public safety broadband network and LMR will not occur until *Mission Critical Push-To-Talk (MCPTT)* is specified and standardized. MCPTT will allow mission critical push-to-talk LMR style communications over an LTE network. The standardization is important since most public safety users do not want to be constrained to one vendor, but would like to be able to mix and match vendors of the PTT devices. This is analogous to current LMR practice, where, in most cases, use of open standards allows purchase of radios from many vendors. In June 2017 an interoperability test of using equipment from over 20 vendors achieved an 85% success rate after over 1000 tests(ETSI (2017)).

FirstNet will also require enhanced security to protect the system from unauthorized users, eavesdropping, denial of service attacks, and other security risks.

8 Open Research Questions

While a base FirstNet will be implemented during 2018, there are still a variety of research questions that need to be answered as the system evolves over the next quarter century. While many research questions involve improvement of the LTE standard itself as discussed in the previous section, there are others that do not directly relate to the LTE standard (Kindelspire (2017), Ross, et al (2017)). These include:

Cellular Systems as Self-organizing Networks Despite the care taken in designing a network, it is likely that, at some point, one or more cellsites will be off the air and unusable. When this happens in a normal cellular network, often the fringe coverage for adjacent cellsites is sufficient that, while the coverage is degraded, it is still acceptable in an outdoor environment. In an urban environment where first responders are expected to be inside a building, this loss of performance will be noticeable. In rural areas there will be a much higher likelihood of service disruption when a cellsite is inoperable.

Understanding Public Safety Grade While cellsites themselves and the network, in general, are built to 99.999% reliability, the outages in disasters are local and could affect a large population. For example, Ross et al. (2017) notes that after Hurricane Irma 50% of the sites in Miami-Dade County were knocked out. While these disruptions would have had little effect on the performance metrics of FirstNet, they had a significant effect on a large population.

Post LTE Roadmap As broadband network standards evolve, so must FirstNet. The next generation of broadband standards, 5G, are being finalized. How will FirstNet evolve to use these standards? During AT&T's Quarterly Earnings call in January 2018, its Chairman and CEO Randall Stephenson said: "What we're doing is building a nationwide network with the latest technology. It's designed and it's hardened for America's first responders, and then that will be our foundation for broad 5G deployment" (Jackson (2018)).

The final question is *Is the political/business model sustainable?* Although public-private partnerships have been around for a long time, the size and scope of this project may challenge these.

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