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Survey of wireless communication technologies for public safety

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Abstract—Public Safety (PS) organizations bring value to society by creating a stable and secure environment. The services they provide include protection of people, environment and property and they address a large number of threats both natural and man-made, acts of terrorism, technological, radiological or environmental accidents. The capability to exchange information (e.g., voice or data) is essential to improve the coordination of PS officers during an emergency crisis and improve response efforts. Wireless communications are particularly important in field operations to support the mobility of first responders. Recent disasters have increased the focus and emphasized the importance of the need to enhance interoperability, capacity and broadband connectivity of the wireless networks used by PS organizations. This paper surveys the outstanding challenges in this area, the status of wireless communication technologies in this particular domain and the current regulatory, standardization and research activities to address the identified challenges, with a particular focus on the USA and Europe.

Index Terms—Wireless communications, Security, Public Safety, Software Defined Radio, Radio frequency spectrum, Cognitive Radio, Interoperability, End User Applications.

I. INTRODUCTION

Public Safety (PS) organizations play a critical role in disaster preparedness and recovery, assisting in the response to emergency events, including catastrophic disasters. Typically, first responders include law enforcement, fire-fighters, emergency medical personnel, and other organizations which are among the first on the scene of an emergency. In large natural disasters, military organizations, volunteer groups, non-government organizations and other local and national organizations may also contribute to disaster response.

Over the last ten years there has been a growing corpus of research on PS organizations and emergency response, and in particular the use of Information Communication Technology (ICT) from a number of perspectives [1-3]. PS organizations and emergency responders are increasingly reliant on ICT infrastructures and services to perform their duties [4]. As in the commercial and military domain, users (workers, managers and decision makers) need to collect, analyze, distribute, share and store information among various entities and different contexts. The challenge of crisis management or disaster management is reducing the impact and injury to individuals, assets and the society. This task requires a set of capabilities, which includes resource management, supply chain management and access to relevant data and communication [5]. Communication is an essential element in various operational scenarios and at different levels of the hierarchy of PS organizations. First responders (i.e., police officers, fire-fighters) should be able to exchange information (i.e., voice and data) in a timely manner to coordinate the relief efforts and to develop situational awareness. In less volatile and fast-paced environments, individuals may have time for reflection and deliberation, however in emergency response timely information sharing and the development of shared situational awareness is critical.

Communications technologies and equipment used by PS organizations are often referred to as Professional Mobile Radio (PMR) or Public safety Land Mobile Radio (PLMR), which refers to wireless systems used by PS agencies for coordinating teams and providing rapid emergency response.

Other authors use the term Public Protection Disaster Relief (PPDR) radio communications, defined as the combination of:

1) "Public protection (PP) radiocommunication: Radiocommunications used by responsible agencies and organizations dealing with maintenance of law and order, protection of life and property, and emergency situations" [6].

2) "Disaster relief (DR) radiocommunication: Radiocommunications used by agencies and organizations dealing with a serious disruption of the functioning of society, posing a significant, widespread threat to human life, health, property or the environment, whether caused by accident, nature or human activity, and whether developing suddenly or as a result of complex, long-term processes".

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Communication capabilities need to be provided in very challenging environments where critical infrastructures (e.g., energy, communications) are often degraded or destroyed by the impact of the catastrophic event. Furthermore, natural disasters or other emergency crisis are usually unplanned events, causing panic conditions in the civilian population and affecting existing resources (e.g., transportation infrastructure), which makes the task of first responders even more difficult. In large-scale natural disasters, many different PS organizations may be involved with different information technology and communication systems. At the same time, commercial communication infrastructure and resources must also be functional in order to alert and communicate with the civilian population.

The presence of different organizations with different communication systems often creates interoperability issues during emergency crisis [4]. In addition, specific security requirements including communication and information protection and partitioning can also exacerbate the lack of interoperability.

As a consequence of changes in working practices and new applications, PS users are requiring wireless broadband network capability in order to stream video, while maintaining a minimum level of availability and reliability [5]. Sharing of various types of data is needed in order to establish and maintain a Common Operational Picture (COP) between agencies and between field and central command staff. The provision of wireless broadband communications requires the availability of radio frequency spectrum bands. However, at present, there is fierce competition for the allocation of spectrum bands, especially in the frequency range below 1 GHz, which has better propagation characteristics and comparatively less cost for the deployment of cellular networks.

This paper surveys the current state of wireless communications technology and the current regulatory, standardization and research activities to address identified challenges with a particular focus on Europe and the USA. By doing so, this paper seeks to be forward looking as much as reporting on the current state in order to advance an enlarged understanding of the current and next generation of PS communications for emergency response.

The remainder of the paper is organized as follows. Section II describes the operational scenarios, and applications, which drive the definition of requirements. The section also identifies the main challenges for PS communications with a special focus on interoperability and lack of broadband connectivity. Section III describes the current communications standards and their features and the existing spectrum regulatory framework to support these standards. Section IV identifies and discusses current trends in the evolution of PS wireless communications. This section also describes the current research projects funded by the European Commission in this domain. Section V concludes the paper.

II. OPERATIONAL CONTEXTS AND REQUIREMENTS

A. PS organizations, functions and scenarios

Various projects (see section IV.B for details) have investigated the operational contexts and requirements of PS organizations and have produced relevant documents and deliverables. In most cases, the deliverables provide results of interaction with End Users aiming to collect the need and lessons learned from real crisis management experiences.

The task of defining a common set of operational and technical requirements for all PS organizations is quite challenging because there are many different entities with various functions and operational scopes.

From [7] and [8], we can identify the following main functions:

- Law Enforcement. Law enforcement is the function to prevent, investigate, apprehend or detain any individual, which is suspected or convicted of offenses against the criminal law.
- Emergency Medical and Health Services (EMHS). The function of medical services is to provide critical invasive and supportive care of sick and injured citizens and the ability to transfer the people in a safe and controlled environment (i.e., to a hospital). Doctors, paramedics, medical technicians, nurses or trained volunteers can supply these services.
- Border security. Control of the border of a nation or a regional area from intruders or other threats, which could endanger the safety and economic well-being of citizens. Border security is usually performed by the police organization or specialized border security guard. The coast guard is a special case of border security.
- Environment protection. This is the function to protect the overall national natural environment or a specific regional area, including its ecosystems composed by animals and plants. This function is limited to the everyday operation of protecting the environment like monitoring of the water, air and land.
- Fire-fighting. This is the function of extinguishing hazardous fires that threaten civilian populations and assets. Hazardous fires can appear in urban areas (e.g., houses or buildings) or rural areas (e.g., forest fires).
- Search and rescue. This function has the objective to locate access, stabilize, and transport lost or missing persons to a place of safety.
- Emergency crisis. Crisis management integrates various functions described above (e.g., search and rescue, EMHS) to support the resolution of a large crisis. Additionally, emergency crisis may also require the creation and maintenance of disaster supply chains, civil engineering and other functions depending on the type of crisis.

Each of the preceding PS functions typical operates in certain operational domains and frames of reference, typically defined as:

- Border area

A border area is identified as the boundary between nations or geopolitical regions. Borders can be across land (i.e., Green border) or across the sea or a major lake (i.e., Blue border). PS organizations in a border area are focused on threats like illegal immigration and smuggling, but they can also be involved in cross-national disaster management (e.g., earthquake, flooding). The difference between Green border and Blue border is the presence of different PS organizations (e.g., Coastal Guard) and different threats.

- Urban environment

An urban environment is identified as an area in a city or a densely urbanized area. This context typically has a high-density of people and buildings, presence of man-made obstacles, limited area of operations (i.e., radius in the range of hundreds meters to a few Kms) and need for fast reaction times by PS officers. Suburban areas share many similar characteristics.

- Port or airport

A port or airport has similar features to the urban environment, with the additional features of a border area. In comparison to a generic urban environment, there is a larger presence of critical facilities (e.g., air traffic control tower) or dangerous materials (e.g., deposit of inflammable substances).

- Rural environment

A rural environment is identified as an area, which is not densely urbanized, such as remote towns/villages in mountainous or forest areas. There may be also be natural obstacles separating the remote town/village such as mountains, deserts and hills and a major metropolitan area or accessible road networks. The area of operations can have a wide geographical extension (i.e., tens of square Kms). A rural environment does not usually have an extensive fixed communication infrastructure and typically suffers from limited network coverage.

Many different types of PS organizations operate in these domains. In some cases, a PS organization provides more than one function and must operate in more than one domain.

Table 1 provides an overview of the most common types of PS organizations, the functions they provide and the domains where they usually operate.
It shows that there is defining characteristics in terms of the frame of reference of the different contexts in which the individual PS organizations operate, with some PS organizations being very specialized in their work functions and domains. At the same time, several PS organizations overlap in both their functions and operational domains.

Table 1 Public Safety organizations, functions and domains

PS Organization	Description	Functions	Domain
Police	The main objective of the police is law enforcement and protection of the citizen, and include amongst other activities, inclusive of: • prevent and investigate crime • apprehend or detain individuals suspected/convicted of offenses against the criminal law • keeping the peace and securing volatile areas	Law enforcement	Urban Environment, Rural Environment, Border area
Fire Services	With variations from region to region and country to country, the primary areas of responsibility of the fire services include: • structure fire-fighting and fire safety; • wild land fire-fighting; • life-saving through search and rescue; • rendering humanitarian services; • management of hazardous materials and protecting the environment; • salvage and damage control; • safety management within an inner cordon; • mass decontamination.	Law enforcement, protection of the environment, search and rescue	Urban Environment, Rural Environment, Port or Airport
Border Guard (Land)	Border guards are national security agencies which perform border control against criminal interdiction, control of illegal immigration and illegal trafficking.	Border Security	Rural Environment, Border area (Green Border)
Coastal Guard	Coast guard services include search and rescue (at sea and other waterways), protection of coastal waters, criminal interdiction, illegal immigration, disaster and humanitarian assistance in areas of operation.	Law enforcement, protection of the environment, search and rescue. Border Security	Border area (Blue border), Port

Forest Guards	They are specialized in the protection of the forest environment.	Law enforcement, protection of the environment, search and rescue.	Rural Environment
Hospitals, field medical responders	Emergency Medical Services (EMS) has the task to provide critical invasive and supportive care of sick and injured citizens and the ability to transfer the people in a safe and controlled environment. Doctors, Paramedics, Medical Technicians, Nurses or Volunteers can supply these services.	Search and rescue. Emergency Medical Services	All domains
Military	Military is the organization responsible for the national defense policy. Because military is responsible for the nation protection and security, it may also supports PS organizations in case of a large national disaster.	Search and rescue. Emergency Medical Services	Rural environment, Border area
Road Transport Police	Transport police is a specialized police agency responsible for the law enforcement and protection of road transportation ways.	Law enforcement	Urban environment, Rural environment
Railway Transport Police	Railway Transport police is a specialized police agency responsible for the law enforcement and protection of railways.	Law enforcement	Urban environment, Rural environment
Custom Guard	They are responsible for monitoring people and goods entering a country. Given the removal of internal borders in the EU, customs authorities are particularly focused on crime prevention.	Law enforcement	Border area
Airport Security	The airport enforcement authority is responsible for protecting airports, passengers and aircrafts from crime.	Law enforcement	Airport

From the domains and functions identified above, four representative operational scenarios are discussed to highlight the communication challenges shared in multi-agency response to emergencies.

- Emergency crisis in urban area

In this scenario in an urban area, or sub-urban area, a crisis (e.g., fire in a building or terrorist attack) requires the usage of existing local wireless communication networks, potentially connected to the PS Command and Control centers. PS officers will probably use dedicated communication networks like TETRA (TErrestrial Trunked RAdio), while Non-Governmental Organizations (NGO) or civilians may use commercial networks like GSM to communicate. Buildings or other obstacles are likely to inhibit (see Figure 1) wireless communication.
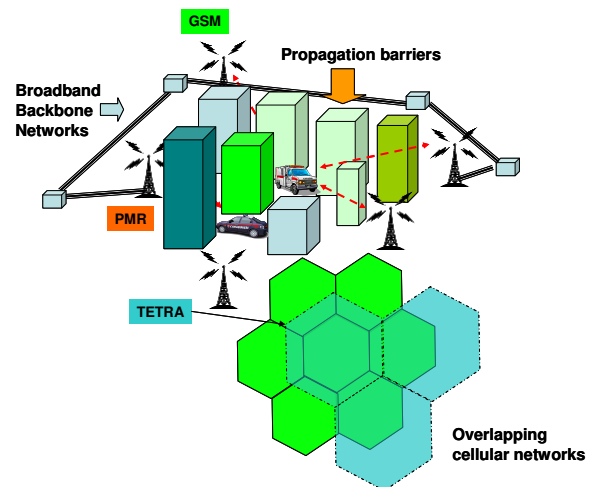
Figure 1 Emergency crisis in urban area

- Large Natural disaster in a rural area.

In this scenario a natural disaster strikes in an isolated area. As described, in such a context the establishment of communication is usually a major challenge because communication infrastructures were either not present in the first place or because they are degraded or destroyed due the crisis (e.g., flooding, earthquake). Further, lack of coverage and traffic capacity is usually a major issue. Response of large-scale natural disasters usually includes the participation of different types of responders from NGO, fire-fighters, police and military over a large geographic area.

and BLACK (security secret level) network, but PS organizations can only communicate on the RED network or with lower levels of security.

Figure 2 Large Natural disaster

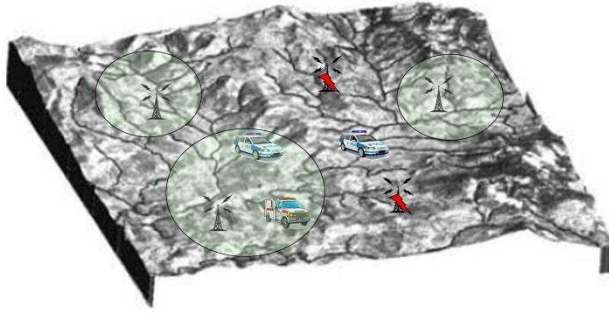• Cross-border law enforcement.

This cross-border scenario involves different nations or geo-political regions and PS organizations. PS organizations are usually equipped with communication systems based on different standards or operate in different frequencies (e.g., TETRA/TETRAPOL). In this scenario, interoperability issues (the inter-exchange between voice and data communication systems) are the main challenge, while traffic capacity is usually well planned.
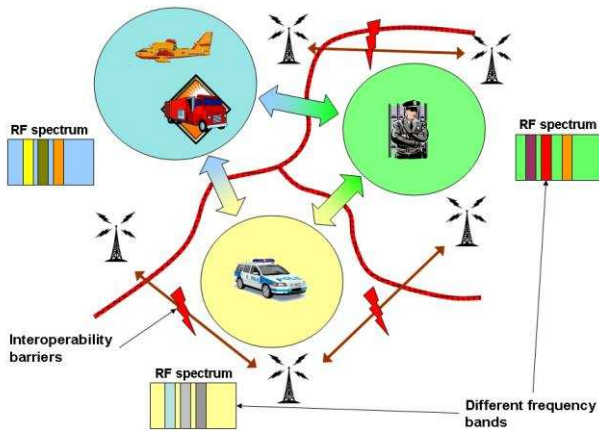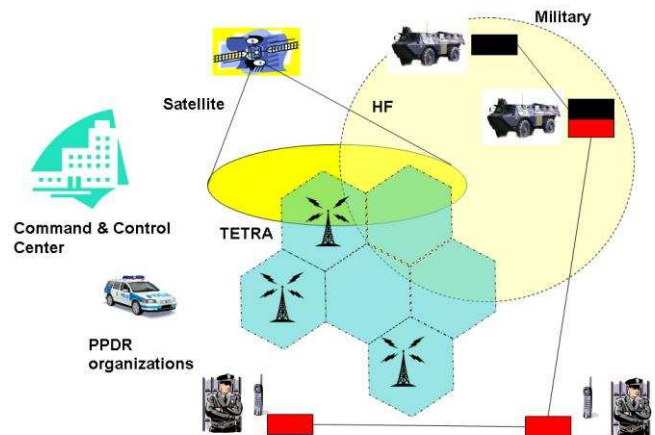

Figure 4 Heterogeneous systems with different security levels

In all the described scenarios, there is also the need to create an information channel to the civilians, through broadcasters (e.g., TV) or commercial communication systems (e.g., Short Message Service to the GSM/UMTS users). Usually, only high level Command and Control centers at national or regional level are authorized to send information to the citizens.

• Major Event.

Major events like a G7 meeting or the Olympic Games involve the convergence of a large number of people, where the risk of criminal activity or disorders and severe disruption is increased. In these events, a large number of PS officers are involved and scalability is often a critical issue. Major events are usually planned and it is possible to augment the communication capabilities in advance.

Figure 3 Cross-border

• Emergency crisis with heterogeneous communications systems with different security levels.

In this scenario, different PS organizations have not only different communication systems, but also different levels of security and their systems use different radio frequency spectrum bands. For example: a joint operation among military and PS organizations, where the military users need to maintain separately a RED (security confidential level) and BLACK (security secret level) network, but PS

• Indoor scenario.

In some cases, PS officers must operate in an indoor scenario like a building or underground station where wireless propagation is strongly hampered by walls and ceilings. In this scenario, communication options are limited and location applications from Global Navigation Satellite System (GNSS) are also unavailable.

B. Communication services and applications

The aforementioned roles and scenarios require various services and capabilities from communication systems.

Different authors and bodies use specific taxonomies of communication services. The SAFECOM program of the US Department of Homeland Security [9] uses the following definitions:

• Interactive voice communications among PS officers.

• Non-interactive voice communications occur when a dispatcher or supervisor alerts members of

a group about emergency situations or acts to share information, without an immediate response being required or designed in the communications.

- Interactive data communications when there is query made and a response provided.
- Non-interactive data communications among PS officers.

Other authors define communication services as [10]:
- Voice
- Video
- Data connectivity
- Broadcast
- Multicast or group communication
- Push-to-Talk

Most of these services are already provided by current telecommunication technologies described in section III.

In this paper, we identify the following basic services for PS communications with the related features:
- Voice. This is the primary form of communication by PS officers in the field. In comparison to commercial networks, voice communication must guarantee a specific level of quality to ensure that the requests and responses among PS officers are clearly understood and they are not ambiguous even in emergency crisis where background noise can be present (e.g., explosions, crowds shouting). For example, [11] has shown that 70% of the PS officers judge that voice quality is acceptable if the packet loss ratio is up to 5% and the packet size is either 10 or 40 ms. Voice can be set up as Group Calls, which is another important concept in PS communications, where a pre-defined group of users can participate in a communication. For example, all the PS officers within a specific hierarchical level.
- Data connectivity. This refers to interactive data communication (i.e., it does not include messaging) between one or more parties. It includes different types of data communication like video streaming, query to remote data servers and others; each of them with specific Quality of Service (QoS) requirements.
- Messaging. This refers to non-interactive data communication and exchange of message among PS officers. The exchange of messages can include text or data. The message can be distributed as broadcast or multicast.
- Push-to-Talk. Is a service which allows half-duplex communication between two PS officers, using a momentary button to switch from voice reception mode to transmit mode.
- Security services. Include the security functions like authentication, authorization, confidentiality integrity and availability.

Security is of primary importance in PS communications because sensitive information could be transmitted among PS officers.

In addition, we also identify the Location service to determine the location of PS officers or vehicles in the field. The Location service can be provided by GNSS like GPS or the future Galileo.

This set of services is used to build more sophisticated applications. In the case of applications built on data connectivity and messaging services, an important requirement on the network is the amount of bandwidth available to support the application. For example: video streaming of a fire building is not usable by PS officers if it is not supported by the network with a reasonable data bandwidth, otherwise the quality and the resolution of the video would not be enough for the operational needs of the PS officers.

Table 2 identifies the main applications and the required data rate. Wideband is in the range of hundreds of Kbit/s, while broadband is more than 1 Mbit/s (as indicated in [12]) for data connectivity.

Table 2 Public Safety applications

Application	Description	Required data rate (Wideband/Broadband)
Verification of biometric data	PS officers may check the biometric data of potential criminals (e.g., fingerprints) during their patrolling duty. The biometric data could be transmitted to the headquarters or a center with the biometric archives and the response could be sent back to the PS officers. This would be a positive method of identification during field interrogation stops if documents are missing.	Wideband
Wireless video surveillance and remote monitoring	A fixed or mobile sensor can record and distribute data in video-streaming format, which is then collected and distributed to PS responders and Command and Control centers.	Broadband
Automatic number plate recognition	A camera captures license plates and transmits the image to headquarters to verify that the vehicles have not been stolen or the owner is a crime offender.	Wideband
Documents scan	In patrolling or border security operations, PS officers can verify a document like a driving license in a more efficient way. Documents scan is also useful in border security operations where people, who cross the borders, may have documents in bad condition or falsified.	Wideband
Database checks	This application area includes	Wideband/

	all the activities where PS officers must retrieve data from the headquarters to support their work.	Broadband
Location/Tracking for Automatic Vehicle/Officer Location. Situation Awareness	The PS officer has a GNSS (e.g., GPS) position localizer on the handheld terminal or the vehicular terminal. The positions are sent periodically to the headquarters so that the command centre can organize and execute the operations in a more efficient way.	Wideband
Transmission of Building/Floor plans	In case of an emergency crisis or a natural disaster, PS responders may have the need to access the layout of the buildings where people are trapped. Building or floor plans can be requested to the headquarters and transmitted to the PS responders.	Broadband
Monitoring of PS officer	Vital signs of PS officers could be monitored in real-time to verify their condition. This is particularly important for fire-fighters and officers involved in search and rescue operations.	Wideband
Remote emergency medical service	Through transmission of video and data, medical personnel may intervene or support the team in the field for an emergency patient.	Broadband
Sensor networks	Sensors networks could be deployed in a specific area and transmit images or data to the PS responders operating in the area or to the command centre at the headquarters. This application does not include video-surveillance, which is described above.	Wideband

In addition to Table 2, other sources have identified the list of current and future PS applications with the associated specifications and technical requirements. In particular the European CEPT FM49 [13] and Analysis Mason [5] have identified applications, which requires broadband connectivity. Reference [14] also identifies similar applications to the ones described in this paper and compares the services provided by PS and commercial networks.

Beyond the technical requirements defined by the current and future applications, PS equipment must validate specific operational requirements, which are also different from commercial equipment.

C. Requirements

Even with such a fragmented market and wide variety of PS end-users, a number of organizations have identified common set of requirements.

The definition of operational requirements is an essential step, which can be based on two phases:
1. The first phase identifies and defines the relationships among authorities and PS organizations during emergencies in term of policies or procedures and required services [15]. Among them there are the procedures involving Public Safety Answering Points (PSAP), emergency control centers, mobile rescue teams and single rescuers or agents.
2. The second phase identifies the operational requirements and the applicable procedures, which can be used to define the technical requirements (e.g., time to deployment, security, interoperability, resilience, connection set-up time, data rate) and the services (e.g., group call, messaging, roaming).

In a similar way, the European Telecommunications Standards Institute (ETSI) EMTEL [15] states that "Technology provides tools to improve the effectiveness and efficiency when handling the tasks and procedures. It can never replace the responsibility of the authorities and the correct application of their agreed procedures in the event *of an incident*"

The SAFECOM program in the US Department of Homeland Security has defined Public Safety Statement of Requirements [9] in 2006, which provides a very detailed description of the operational scenarios and related requirements, with a specific focus on interoperability. The first volume of [9] defines the following operational requirements:
- Support to Command and Control hierarchy
- Support to interactive and non-interactive voice and data communication
- Inter-agency interoperability
- Security
- Support to a new data applications, which go beyond simple voice communication

The second volume of [9] defines the technical requirements:
- Speech transmission performance
- Video transmission performance
- QoS (packet loss, jitter, latency)
- Timeliness in the delivering messages
- Radio coverage
- Call prioritization
- Robustness of PS equipment
- Energy consumption
- Security
- Availability

Technical requirements are also defined as part of the standardization process for wireless communications technologies in form of technical specifications.
ETSI, Technical Reports ETSI TR 102 021(1-8) [16] define technical requirements for TETRA wireless communication

technology, which is predominantly used in Europe. ETSI TR 102 745 [8] defines user requirements for the potential application of Software Defined Radio (SDR) and Cognitive Radio (CR) technology in PS domain. ETSI Project MESA defines operational and technical requirements in [7] for generic PPDR wireless communications.

In general, operational and technical requirements specified for PS communication equipment are more stringent and severe than the commercial equipment, which is one of the main reasons why PS market is considered a niche market in comparison to the commercial market.

Drawing on [17], we identify two main examples of these differences:
- Call setup time is usually below 300-400 milliseconds, which is much shorter than the call setup in commercial networks.
- Calls Prioritization is needed to grant network access to specific users in case of emergency. This service is also not currently provided by commercial networks even if the LTE standard has provision for this service in the standard (see section IV on future developments).

Further discussions on the differences between PS, military and commercial markets are described in more detail in the next section.

D. Business considerations and market comparison with commercial and military domains

PS organizations and relevant technologies applications compose a domain which may be quite different with respect to the commercial or military domains regarding different aspects. The main difference is in the business model involving the end user. PS networks and terminals are usually financed with government funding and they are planned for longer life spans (i.e., 10-15 years) than commercial networks, which also raises the problem of technological obsolescence in comparison to commercial networks. An additional important difference concerns the communication facilities and the related use. A PS operator may rely on both public (e.g., GSM, wired telephone network) and private dedicated networks (e.g., TETRA, private mobile V/UHF radio) for routine activities, including training. But for crisis emergency communications, PS users may adopt ad-hoc like networks for connecting the local crisis area to backbone fixed networks. Furthermore, the size of the PS market in terms of number of terminals and network equipment is much smaller than the commercial market. In many cases, this aspect precludes the possibility of creating a mass market and lowering the cost of the equipment to similar values of the commercial domain. In comparison to the military domain, PS, civilian and military markets share some common elements but they also have significant differences:

- The Commercial market is based on economy of scale: the number of existing cellular phones is exceeding four billion devices, which is many orders of magnitude larger than the PS market or the military market. Non-recurring costs for cellular phones are largely based on the design of the Application-Specific Integrated Circuit (ASIC) components. These costs are minimized by the huge number of devices sold on the market (even for a single manufacturer). The civilian market is based on few wireless communication standards: GSM, UMTS, WiFi, and LTE (in the future).

- The Military market is not based on an economy of scale but they benefit by very large budgets especially in the US. The large budget is usually justified by stringent operational requirements (e.g., security, frequency hopping) which do not exist in the commercial market. For instance, the Joint Tactical Radio System (JTRS) program cost 6.8 billion (USD), and the price of a single terminal is obviously orders of magnitude larger than commercial cellular phones. There are various wireless commercial systems in the Navy, Army and Air force: from ground tactical system, to HF long distance communications, to Air-Ground communications and even satellite communications.
Most of the military communications are link-based or tactical network, because they are designed to operate without an existing fixed infrastructure. Because the military forces operate in hostile territory, they do not have a fixed infrastructure in place or they cannot use it. Civilian cellular networks and TETRA cellular PS networks are obviously based on fixed infrastructures and they have more complex protocols to set-up the connections or allocate the resources.

On the other hand, the military market shares some features with the PS market: they are both government funded and they usually share the same network manufacturers. In Europe, EADS, Thales, Rohde & Schwarz, Indra and Finmeccanica provide networks and terminals both to military and PS organizations. There are also stronger synergies in the operational and technical requirements including security requirements. It is also worth recognizing that some national PS organizations are almost considered military organizations (e.g. Carabinieri in Italy) and they share network equipment and operational procedures with their military counterparts.

- PS market is usually considered as a niche market because of the smaller volume of networks and terminals in comparison to the civilian market and smaller budget in comparison to the military

budget. PS networks (e.g., as the one based on TETRA standard in Europe) are usually dedicated networks: they are specifically built and dedicated for one or more public safety organizations (e.g., fire-fighters). The extension of these dedicated networks to other PS organizations (e.g., ambulances) must be agreed and regulated at government level.

As described before, the PS market is highly fragmented. The main wireless communication systems are TETRA, TETRAPOL in Europe and APCO 25 (Association of Public-Safety Communications Officials) in USA. Other communication systems include Analog Mobile Radio, Digital Mobile Radio (DMR), satellite communications and even commercial systems. In some countries (e.g., Finland), the government has managed to adopt a single communication system for various organizations (i.e., fire-fighters, police, ambulance) but this is not a usual situation. As in the case of civilian markets, the building and deployment of PS networks is very expensive even if the spectrum license fees are usually waived for public interest.

III. TECHNOLOGY STANDARDS AND REGULATORY FRAMEWORKS

In recent years, most of the PS organizations around the world have replaced their legacy wireless communication equipment based on analog technology with new digital wireless communication systems. Three sets of standards have become predominant: TETRA and TETRAPOL (i.e., European standards) in Europe and APCO 25 in USA (i.e., an US standard). Beyond these three main standards, various wireless telecommunication systems are used by PS organizations depending on their role, their level of technological progress and their operational needs and so on. In this category, PS officers can use analog PMR, Satellite Communications, and communications in HF/VHF bands for terrestrial, maritime and avionics or even commercial communication systems.

The deployment of PS networks is obviously related to the existing national or international regulatory frameworks. In particular, radio frequency spectrum regulations identify the spectrum bands, which PS networks are allowed to use. In some case, spectrum regulations can limit the bandwidth available for data communication and services.

The purpose of this section is to describe the current PS technological standards for wireless communications and the related spectrum regulations. The response to large natural disaster also sees the participation of military organizations with their own communications systems including HF, UHF and tactical networks but the description of specific military communications systems is out of scope of this paper.

A. Wireless Communication technologies

1) TETRA

TETRA is a telecommunications standard for Private Mobile Digital Radio systems developed by ETSI to meet the needs of traditional PMR user organizations. TETRA is an interoperability standard that allows equipment from multiple vendors to interoperate with each other. One of TETRA's key strengths is its ability to scale, from a few dozen to hundreds of thousands of users across an entire continent [18] and its features such as talk groups. A primary talk group feature is handling large groups (up to 200 users), multiple group membership (users can belong to many groups), and participant status (where members of a talk group can identify who is speaking on a talk group call).

Since the first generation of networks was deployed in 1997, hundreds of TETRA networks have been deployed across the world mostly in Europe (www.tetramou.com). TETRA standard defines the air interface and the interface between the TETRA network and ISDN, PSTN, PDN, PABX and other TETRA systems. The standard also includes the specifications of all basic and advanced services for a TETRA network. The TETRA standard defines the following basic services for voice and data:

- Tele-services
- Bearer services
- Supplementary services

A "Tele-service" is a system service as seen by the end user through the Man Machine Interface (MMI) (e.g., a keyboard). An individual call or a group call is a tele-service, invoked for instance by keying the call button on the MMI. Tele-services includes: individual call (point-to-point), group call (point-to-multipoint), acknowledged group call and broadcast call (point-to-multipoint one way). A "Bearer service" provides communication capability between terminal network interfaces, excluding the functions of the terminal. The following services are provided: individual calls, group calls, acknowledged group call, broadcast call. Data rates are from 2.4 Kbits to 28.8 Kbits. A supplementary service modifies or supplements a bearer service or tele-service with access priority, pre-emptive priority, priority call, talking party identification and other services.

TETRA has been designed on the basis on PS operational requirements mentioned in II.C.

TETRA is also equipped with strong security features for authentication, authorization and confidentiality. Some key security features include air interface encryption and end to end encryption. In addition the capability for mutual authentication of mobile by network and network by mobile is also privided. Related functions include the options for Over The Air Reckeying (OTAR).

This new release of TETRA: TETRA Release 2, generally referred to as "TEDS" or TETRA Enhanced Data Service

[19], already published by ETSI provides enhanced packet and data service with data rate up to 473 Kbits/s [20] (see Table 3 for TETRA Rel 1 vs TEDS). In designing the physical layer and the higher layer protocols for the Release 2 standard, special care has been taken to guarantee maximum backward-compatibility with the existing TETRA Voice+Data (Release 1) standard. Every "TEDS" enabled TETRA Mobile Station (or terminal) may access all traditional TETRA services above defined.

TETRA TEDS has been developed to supply PS organizations with wideband data connectivity and in some European countries, spectrum bands have been allocated to support this standard [21] but these bands are not harmonized yet.

Table 3 TETRA Rel 1 vs TEDS

Features	TETRA 1	TEDS
Channel access	TDMA	TDMA
Modulation	π/QPSK	4/16/64/QAM
Carrier bandwidth	25 KHz	25/50/100/150 KHz
Channels/carrier	4	4
Modulation and Coding		Throughput
TETRA 1 all 4 slots, 25 KHz		10 Kb/s
TETRA 4QAM, r=1/2, 50 KHz		26 Kb/s
TETRA 16QAM, r=1/2, 50 KHz		51 Kb/s
TETRA 64QAM, r=12/3, 50 KHz		103 Kb/s

Dedicated TETRA networks are already deployed in European member states or they are being deployed. For example, the UK has one of the world's largest deployments for PS organisations [22] , where TETRA network consists of more than 3000 base stations ensuring national coverage [23] across Police Fire, Ambulance and other specialised groups in the UK use Airwave Tetra.

TETRA can be used (and it is currently used) in most of the scenarios identified in II.A, even it requires a fixed infrastructure, which can be degraded or destroyed as in the scenario Large Natural disaster in a rural area.

Because of the security features, TETRA is particularly relevant in the scenario *"Emergency crisis with heterogeneous communications systems with different security levels"* and interoperability of the different security framework can create interoperability barriers even if the radio access technology is the same (i.e., TETRA).

2) APCO 25

APCO 25 is a standard for digital wireless communication for PS domain. APCO 25 is mostly used in the USA. The standards have been developed together with the Telecommunications Industry Association (TIA). Four key objectives guided the steering committee in the definition of the standards:

- Provide enhanced functionality with equipment and capabilities focused on PS needs;
- Improve spectrum efficiency in comparison to previous communication systems (i.e., analog PMR)
- Ensure competition among multiple vendors through Open Systems Architecture
- Allow effective, efficient, and reliable intra-agency and inter-agency communications.

APCO 25 is based on the Frequency Division Multiple Access (FDMA) access method and QPSK-C modulation. The protocol supports encrypted communication. Radios can communicate in analog mode with legacy radios, and in either digital or analog modes with other APCO 25 radios. APCO 25 provides voice and limited data rate communications up to a maximum of 9.6 Kbits/s. An evolution of APCO 25 is currently under development to provide broadband connectivity. APCO 25 provides a rich set of services including messaging, group calls, broadcast call and others. Because APCO 25 is based on a fixed network infrastructure, the coverage is based on the extension/deployment of the infrastructure. Usually a base station provides coverage of 4-5 Kms.

APCO25 has been designed on the basis on PS operational requirements mentioned in II.C.

Like TETRA, APCO 25 can be used (and it is currently used) in most of the scenarios identified in II.A, even it requires a fixed infrastructure, which can be degraded or destroyed as in the scenario Large Natural disaster in a rural area. Similar considerations for security are also valid for APCO 25.

3) TETRAPOL

TETRAPOL was developed for PS usage on the requirement of the French police forces. Even though the name of the product is similar to TETRA, TETRAPOL is quite different from the ETSI TETRA standard. TETRAPOL is a proprietary solution from EADS Telecom (formerly Matra) and has never been accepted as an ETSI standard.

TETRAPOL uses FDMA technology providing one speech or control channel per 12.5 kHz carrier [24]. TETRAPOL provides voice connectivity and limited data connectivity like TETRA release 1, although investigation of the performance of both systems in specific conditions concluded that TETRA has better performance than TETRAPOL [25]. Like TETRA, TETRAPOL provides a rich set of services including messaging, group calls, broadcast call and others. Because TETRAPOL is based on a fixed network infrastructure, the coverage is based on the extension/deployment of the infrastructure. Usually a base station provides coverage of 4-5 Km.

TETRAPOL has been designed on the basis on PS operational requirements mentioned in II.C.

A TETRAPOL base station can handle up to 24 radio channels. The TETRAPOL channel access is based on FDMA with a channel spacing of 12.5 kHz. The gross modulation bit rate is 8 Kbit/s using binary Gaussian Minimum Shift Keying (GMSK) modulation.

Like TETRA, TETRAPOL can be used (and it is currently used) in most of the scenarios identified in II.A, even it requires a fixed infrastructure, which can be degraded or destroyed as in the scenario Large Natural disaster in a rural area. Similar considerations for security are also valid for TETRAPOL.

4) Satellite Networks

Satellite networks provide the advantage that they do not rely on an existing terrestrial infrastructure. Satellite networks can transmit in various frequency bands (e.g., C-Band, Ku Band) and they generally provide extensive coverage. Satellite terminals can be fixed like the Very Small Aperture Terminal (VSAT) or mobile. Fixed terminals usually provide higher data rates (in the order of 1.5 Mbits or more) than mobile terminals (in the order of 256 Kbits). Mobile Satellite Services (MSS) are satellite systems based on portable terrestrial terminals. MSS terminals can be installed on trucks, automobiles, ships or even airplanes. MSS terminals can be an important asset in the PS domain by providing almost full coverage with the additional benefit of mobility.

Because satellite networks are not dependent on a terrestrial fixed infrastructure and they usually have a very large coverage, there are particularly adept to support PS organizations in specific scenarios like natural disasters (see section II.A), where they can be used to provide direct connectivity between the PS officers in the field and the remote control centers. In particular, satellite communications can be used to deploy ad-hoc networks in an area struck by a disaster or in a remote area where there was no fixed infrastructure in first place.

An example of such infrastructure is described in [26], which proposes a hybrid satellite and terrestrial system architecture for emergency mobile communications. The architecture is based on MSS coupled with an extension of 802.11 based on the Hybrid Wireless Mesh Protocol (HWMP). The authors in [26] correctly indicate that mobility management is an essential function in this architecture and they focus on the two components of location management and handoff management.

Satellite communications were also used in the 2008 earthquake in the Chinese Sichuan Province, as reported in [27]. The paper concludes that in the aftermath of the Wenchuan Earthquake, only satellite communication could function properly in certain places due to blocked roads and bad weather.

In [28] the application of High Altitude Platforms (HAP) is presented. HAP's are quasi-stationary aerial platforms operating in the stratosphere at an altitude between 17 and 22 km, for disaster response. The proposed architecture is based on three main components: a) satellite communications, b) the HAP, and c) a communication facility which guarantees the connection (possibly through a satellite/HAP), between the emergency control center (ECC) and the PS officers in the emergency area.
Reference [28] also describes the technical requirements for the proposed systems, indicating that some requirements of PS communications like the fast call setup time may be difficult to implement due to the long distances the satellite communications signal has to cover.

In [29] is proposed a satellite-based communication system for emergency networks. The paper proposes underlay transmission of low power emergency signals in the frequency band of a primary transparent satellite telecommunication or broadcast system. Wideband spreading is used to guarantee that the primary system performance is not affected by the inter-system interference. The paper shows that end-to-end communication is possible with low data rates (i.e., 20 Kbits/s). While this data rate is not optimal for large disaster response operation, it can be used for search and rescue operation in remote areas.

Satellite communication for emergency communications is also the objective of various standardization bodies including ETSI SatEC. The ETSI Technical Report [30] outlines the concept of Emergency Communication Cells over Satellite (ECCS), which is described as temporary emergency communication cell supporting terrestrial wireless and wired standard(s) which are linked/backhauled to a permanent infrastructure and the remote Command and Control center by means of bi-directional satellite links.

Satellite communications have clearly an advantage in scenarios like Large Natural disaster in a rural area, where the absence of a fixed communication infrastructure (because missing or destroyed) does not hamper satellite communications. A downside in the other scenarios is that satellite communications are expensive to use, not sustainable beyond short-term use, and suffer from limited capacity for handling simultaneous calls (although advances in satellite phones capable of terrestrial GSM wireless service are becoming available as described in [31].

Another issue is that satellite networks are not always designed on the basis of the requirements mentioned in II.C. For example, security requirements must often be addressed through end-to-end specific security solutions. In addition, timing requirements for data connectivity are difficult to implement because of the long distances from ground to satellite

5) Digital Mobile Radio

DMR is a new European standard, produced by ETSI [32], defining a direct digital replacement for analogue PMR. DMR can be used in an unlicensed mode (in a 446.1 to 446.2 MHz band) or licensed mode, subject to national frequency planning. Its development is based on three 'tiers':

- Tier 1 is the low-cost, license-exempt digital PMR
- Tier 2 is for the professional market offering peer-to-peer mode and repeater mode (licensed)
- Tier 3 is for trunked operation (licensed)

DMR promises improved range, higher data rates, more efficient use of spectrum, and improved battery in comparison to analog PMR. DMR has been designed to fit into existing licensed PMR bands, meaning that there is no need for re-banding or relicensing.

DMR has been designed on the basis on PS operational requirements mentioned in II.C.

DMR can be used for local communication in any scenarios identified in II.A because it does not require a fixed infrastructure.

6) Avionics communications & Marine communications
The traditional avionic communications are in the VHF band (e.g., 118-136 MHz) and are usually used by PS officers to communicate with helicopters during rescue operations for voice. New standards and technologies have been recently developed, which can be used in PS scenarios.
First responders experience the need of airborne communication during disaster relief. For instance, after a hurricane hitting a wide section of terrestrial communications networks can be severely debilitated.
Damage to first responder networks causes multiple problems in command, control and rescue operations and an Airborne Communication Node (ACN) for emergency communications has great potential for mitigating these problems and assisting in a catastrophic event [33].

As described in [33], different configurations can be adopted according to the specific network re-establishment, in turn affecting the required aircraft payloads capabilities. In fact we can envisage three main configuration options: 1) the system can be deployed as an aircraft repeater, 2) a complete system on an aircraft or 3) a Base Transceiver Station (BTS) on an aircraft. Using any of these options for the ACN, it is possible to provide in-network and out-of-network calls using an ACN.
The three options can be applied for both the re-establishment of 2G/3G cellular communications and for repeater or BTS for interrupted terrestrial PLMR communications.
Concerning PLMR communications, the TETRA standard has already been employed for airborne environment as the TETRA standard includes specific elements for airborne use. Helicopters are becoming an increasingly important part of all PS operations, so it is common for TETRA radios to be used on them.
In order to make compatible the avionic link with the cellular based terrestrial coverage a specific solution has been envisaged. In fact, even at modest altitudes the line-of-sight propagation path can result in interference problems where the frequency plan is based on the assumption of

propagation characteristics associated with terrestrial access (see Figure 5).

Figure 5 Inter-cell long range interference

A common solution is to include a separate frequency layer used exclusively by airborne TETRA equipment. It makes sense, therefore, to allow access from much greater ranges since this reduces the number of sites requiring base radios for the airborne frequency layer.
Thus TETRA Release 2 includes modified burst structures with extended guard periods, in turn allowing access from a little over 80 km. It ensures that the airborne radio terminal affiliates to ground base station(s) specifically designated for use with aircraft (see Figure 6).
It results in a potential reduction by half of the number of base radios required for the airborne frequency layer.
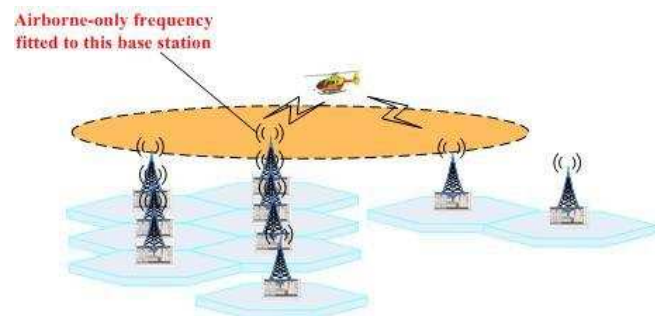

Figure 6 Airborne-only frequency layer

Marine communications are used by the Coast Guard in Blue border scenarios. Beyond coastal guard, marine communications is used for a wide variety of purposes, including summoning rescue services and communicating with harbors, locks, bridges and marinas. Usually it operates in VHF frequency range, between 156 to 174 MHz.

Avionics and Marine communications are generally used in scenarios like Large Natural disaster in a rural area where there is the need to provide coverage over a large area.

7) Commercial cellular wireless communication systems
Commercial cellular wireless communication systems like GSM/GPRS and UMTS have not been designed for PS

purposes and the requirements mentioned in section II.C as they lack the level of reliability, availability, responsiveness and security requested by PS organizations. Nevertheless, there are PS organizations in the world, which do use commercial cellular wireless systems because of lack of alternatives in the area, where they operate or for non-mission critical applications (i.e., GPRS Airwave in UK). In comparison to commercial networks, PS organizations have a high cost per subscriber in the dedicated PS network because the overall number of subscribers is small in comparison to the cost of the network. Obviously PS networks are designed for the protection of the citizen or the nation and not on business requirements [34].

The recent evolution of commercial cellular networks has resulted in high spectrum efficiency and increase bandwidth. Cellular networks have started to become an option for PS users to reduce the cost per subscriber. An important advantage of modern cellular networks is represented by the capability to provide high data rate communications. The High Speed Packet Access (HSPA) is a collection of two mobile telephony protocols HSDPA (High Speed Downlink Packet Access) and HSUPA (High Speed Uplink Packet Access), which extend the performance of existing Wideband Code Division Multiple Access (WCDMA) protocols.

The next generation of commercial cellular networks is represented by Long Term Evolution (LTE) which is able to provide broadband connectivity (e.g., from Mbits/s to tens of Mbits/s and a wide range of services). Some of these services can be dedicated to the PS domain: the Priority Service and Multimedia Priority Service, the Voice Group Call Service (VGCS) for public authority officials, the transferring of emergency call data and the Public Warning System.

The FCC white paper for Public Safety Nationwide Interoperable Broadband Network [35] recommends an approach for public safety broadband communications that leverages the advantage of LTE technologies and standards for the radio access network. There is indeed strong pressure from network manufacturers for the adoption of LTE in the PS domain. As described in [34], the system architecture for PS communication realized with IMS (IP Multimedia Subsystem), the cellular standards of 3GPP and packet switched transmission. The authors in [34] acknowledge that requirements on a PS communication system are in many aspects more restrictive than on commercial systems (i.e., coverage, latency, capacity) and they provide an analysis of the LTE architecture to address these requirements.

Further details on the adoption of LTE technology are provided in section IV.

8) Wireless Local Area Network (WLAN) technologies and MANET

An alternative to satellite communications are wireless, mobile temporary and ad-hoc communication infrastructures as described in [36][37][38] . These are most useful in emergency response where temporary coverage is needed in an expedited manner. In an example of the application of such networks, WiMAX networks supported telecommunications destroyed in the 2004 tsunami in Indonesia and after hurricane Katrina in the Gulf Coast in 2005 [39]. More recently, after the Haiti earthquake the International Telecommunications Union (ITU) led a project that used WiMAX and WiFi technology to rapidly set up wireless phone and Internet connectivity at 100 holding centers for displaced people [40]. Further, there have been advances in these "hybrid" wireless systems, which have developed and deployed in various EU projects. For instance, the WISECOM project, focused on rapidly deployable lightweight communications infrastructures for emergency conditions, (www.wisecom-fp6.eu/) using rapidly deployable communication infrastructures involving a blend of terrestrial mobile radio networks such as GSM, UMTS, WiFi, WiMAX and TETRA over satellite.

A type of ad-hoc wireless typology that is particularly relevant in the context of PS and emergency response is the use wireless/ mobile ad-hoc networks, referred to as MANET's (also sometimes named "opportunistic networks"). MANETs are self-organised mobile networks in which nodes exchange data without the need for an underlying infrastructure and share data in a "mesh" type of network. In this typology, data is shared in a multi-hop manner by being passed between devices, with each device having the potential of routing data to another device. The devices in the network are self-configuring as the network automatically reconfigures when devices move in and out of range. Given the mobility of the nodes the network typology may change rapidly and unpredictably over time [41]. Applications for MANET's have been identified in areas where there is inadequate telecommunications infrastructure [42] .

MANET's can be thought of as an autonomous collection of mobile nodes that communicate over bandwidth-constrained wireless links [41]. There has been interest in MANET for some time in emergency response situations; the number of projects such as WIDENs, which uses the notion of ad-hoc networks to develop a highly reliable communication system to support real-time applications to allow more efficient team collaboration in emergency response scenarios testify to the interest in its use [43]. Others have referred to the use of ad-hoc networks in emergency response as a perfect match [41]. Despite this, its use in live deployment scenarios remains limited. Making use of the concept of wireless mesh networks, the DUMBO project in Thailand used lightweight portable mobile nodes to broaden coverage and penetrate deep into areas not accessible by roads or where the telecommunication infrastructure has been destroyed. During the trials, laptops were carried on elephants to extend the wireless mesh network coverage utilizing hybrid Wi-Fi and satellite connectivity [44]. See [1] for discussion.

In [45] is described a mesh network, which employs one of two connection arrangements — full mesh or partial mesh. The advantages and disadvantages of the two approaches

are investigated. In the full mesh network, each mobile device is connected directly to each of the others. In the partial mesh network, some mobile devices are connected to all the others, while other devices are linked only to the devices with which they exchange the most data. The trade-offs are discussed in the paper. The full mesh network is more resilient because two mobile devices could recreate a new multi-hop connection in case of link failure. The trade-off is that a full mesh network use more communication resources. The paper provides a comparison of the performance in a typical operational scenario. The paper also correctly points out that limited scalability and capacity, combined with the lack of QoS guarantees, are currently the strongest limitation for the adoption of wireless mesh networks in the public safety domain.

A VANET is a sub-type of MANET based in vehicles where the nodes in the network are both vehicles and fixed base station infrastructure. The difference with the MANET is that vehicle can support mobile devices with increased power or performance because they can be powered by the vehicle engine. VANET could also be more appropriate for PS operational scenarios because PS officers use vehicles in their operational scenario.

In addition, WLAN and MANET can also be used integrated with wireless communication technologies described before. In [46] the authors describe a novel solution for integrating WLAN and TETRA networks. The specified solution allows TETRA terminals to interface to the TETRA Switching and Management Infrastructure (SwMI) over a broadband WLAN radio access network,

instead of the conventional narrowband TETRA radio network. The solution provides fully interoperability with TETRA terminals can employ all TETRA services, including group calls, short data messaging, packet data, and so forth.

Similar integration are possible (and they have been described in the previous sections of this paper) with satellite communications or Cellular networks.

As pointed out above, VLAN and MANET networks based on commercial technologies (e.g., WiFi) usually are not designed on the basis on PS operational requirements mentioned in II.C, which makes more complex their deployment in the PS scenarios identified in II.A. For example, security and scalability of the network are major concerns. Nevertheless, the limited cost and flexibility of VLAN and MANET technologies can be advantageous in scenarios where a fixed infrastructure is not present of where the crisis area is limited like in Large Natural disaster in a rural area (only for small areas in the larger scenario) or Indoor scenario.

9) Summary on communication technologies.

Table 4 summarizes the wireless communication systems used by PS organizations. The table also provides the relevance of the technologies to the operational scenarios described in section II: a) Emergency crisis in urban area, b) Natural disaster in a rural area, c) Cross-border law enforcement, d) Emergency crisis with heterogeneous communications systems with different security levels, e) Major Event and f) Indoor scenario.

Table 4 Wireless communications technologies for Public Safety

Technology	Voice	Data Communications	Special services (Group Calls, Messaging, Broadcast)	Coverage	Current Deployment	Robustness/ Availability/ Security	Operational Scenarios
Analog PMR	Yes	No	No	2 Km	Extensive	Limited	a, b,c
DMR	Yes	Yes. Limited	Messaging	2 Km	Limited	Limited (security)	A,b,c,d,e
APCO25	Yes	Yes. Limited (20-30 Kbit/s)	Yes	Depending on the fixed cellular network	USA	Yes	A,b,c,d,e,f
TETRA V.1	Yes	Yes. Limited (20-30 Kbit/s)	Yes	Depending on the fixed cellular network	Europe and some parts of the world	Yes	A,b,c,d,e,f
TETRA V.2 (TEDS)	Yes	Yes. Medium (120 Kbit/s)	Yes	Depending on the fixed cellular network	Limited	Yes	A,b,c,d,e, f
TETRAPOL	Yes	Yes. Limited (20-30 Kbit/s)	Yes	Depending on the fixed cellular network	Some parts of Europe	Yes	A,b,c,d,e, f
GSM/GPRS /UMTS/3G	Yes	Yes. High (Mbit/s)	Limited	Depending on the fixed cellular network	Global	No	A,b,d,e
LTE	Yes	Yes. Very High (Tens of Mbis/s)	Yes	Depending on the fixed cellular	Limited	Limited	A,b,d,e

				network			
Satellite Networks	Yes	Yes. Medium (100 Kbit/s-1 Mbi/ts)	Very Limited	Ubiquitous	Global	Yes (it does not depend on a fixed infrastructure)	B,d
WiFi/WiMax	Yes (VOIP)	Yes. High (Mbit/s)	No	Local (300 Meters from access point)	Global	No	A,b,d,e
Ad-hoc Networks	Yes (VOIP)	Yes. High (Mbit/s)	No	Local (up to 1 Km)	Limited	Limited	A,b,d,f
Marine Communications	Yes	Yes. Limited and for specific applications.	No	Up to 30-40 Km	Global	Medium	B,d,
Avionics Communications	Yes	Yes. Limited and for specific applications.	No	Up to hundreds of Km	Global	Medium	D,d,e

B. Radio frequency Spectrum regulations

Spectrum regulators allocate spectrum bands to PS organizations in similar way to the spectrum allocation in the commercial domain. A significant difference is that PS spectrum bands may not be harmonized across nations for historical reasons. In this section we will describe the spectrum regulatory frameworks for Europe and USA.

1) Europe

In Europe, in 2008 ECC/CEPT5 committee provided a decision on the harmonization of frequency bands for the implementation of digital Public Protection and Disaster Relief (PPDR) radio applications in bands within the 380-470 MHz frequency range (ECC/DEC/(08)05) [47]. This ECC Decision covers narrow band6 as well as wide band7 PS radio applications. Spectrum within the duplex bands 380-385 MHz/390-395 MHz has been designated for narrow band PS radio applications.

The provisions of the above ECC Decision regarding the wide band systems are based on a "tuning range[8]" concept, which provides flexibility for the administrations by implementing this Decision (within the tuning range on a national basis). The aim is to make radio spectrum available for wide band PS radio applications either in the 385-390 MHz/395-399.9 MHz sub bands, in the 410-420 MHz/420-430 MHz sub bands or in the 450-460 MHz/460-470 MHz sub bands. In the same period CEPT developed ECC Recommendation 08-04 concerning frequency bands for the implementation of Broad Band Disaster Relief (BBDR) [48], which recommends that administrations should make available at least 50 MHz of spectrum for digital BBDR radio applications. However, this spectrum is shared with radio LANs and should be available for disaster relief during major incidents.

Therefore, a real harmonized band at European level exists only at the narrow band level and currently it is quite difficult to identify new harmonized bands across Europe below 1 GHz.

The allocation of future bands for Broadband communications in Public Safety is currently investigated in CEPT FM49 [13]. Various options are currently investigated, but the most probable are in: a) the 400-470 MHz band, which has the advantage of being relatively near the current TETRAPOL and TETRA allocation and b) the 694-790 MHz band, which is currently used for TV broadcasting in Europe but could be allocated to the mobile services after 2015 [49]. The option a) has the advantage to be in the adjacent frequency bands of the current TETRA and TETRAPOL allocation, but harmonization across Europe is quite difficult. Option b) will require a second digital dividend with a reallocation of TV broadcasters, which may not supported by some national spectrum regulators.

The current time plan of CEPT FM 49 is to create an ECC report at the end of 2013 to address the development of a European harmonized regulatory framework for broadband PS to maximize interoperability and the end of 2014 a new ECC decision of an amendment of ECC/DEC/(08)05 for the allocation of spectrum bands for broadband connectivity for Public Safety in Europe.

2) USA

In USA, the spectrum allocation is fragmented among many municipalities and in various frequency bands. As described in [50], because of this fragmented approach, PS agencies build more infrastructure than they should and consume more spectrum than they should, even if the overall spectrum allocation is greater than Europe. Table 5 provides a comparison between spectrum band allocations in the USA and Europe (see also [12]).

Innovative approaches for spectrum allocation to public safety have been also recently proposed and they are discussed more in detail in IV.A.3).

Table 5 Radio Frequency Spectrum for PPDR
(* denotes approximate available bandwidth)

PSS Spectrum Allocations

	United States		Europe	
Frequency band	Tuning Range (MHz)	Available Bandwidth (MHz)	Tuning Range (MHz)	Available Bandwidth (MHz)
VHF Low band*	25-50	6.3		
VHF High Band*	150-174	3.6		
220 MHz band*	220-222	0.1		
UHF band*	450-470	3.7	380-385 390-395	5 5
700 MHz band	764-776 794-806	12 12		
800 MHz band*	806-821 821-824 851-866	1.75 3 1.75		
NPSPAC band	866-869	3		
4.9 GHz band	4940-4990	50	Under consideration	
Total		97.2		10

3) International level

Finally, at the international level, the following ITU Reports are relevant to the current analysis:

- Report ITU-R M.2033 on "Radiocommunication objectives and requirements for public protection and disaster relief" (2003) was developed in preparation for WRC-03 and defines the PPDR objectives and requirements for the implementation of future advanced solutions.
- ITU Resolution 646 (WRC-03, Geneva) on "Public Protection and Disaster Relief" strongly recommends using regionally harmonized bands for PPDR radio applications to the maximum extent possible.
- ITU Resolution 647 (WRC-07, Geneva) on "Spectrum Management Guidelines for Emergency and Disaster relief radiocommunication" encourages administrations to consider global and/or regional frequency bands/ranges for emergency and disaster relief when undertaking their national planning and to communicate this information to the Radiocommunication Bureau of the ITU. A database system has been established and is maintained by the Radiocommunication Bureau.

IV. POTENTIAL EVOLUTION OF COMMUNICATION TECHNOLOGIES IN THE PS DOMAIN

A. Future wireless communication technologies

New communications technologies have been proposed for the evolution of public safety communications. While this paper is a survey of the existing PS wireless communications technologies, the objective of this paragraph is to provide a brief overview of the potential evolutions.

Finally, this section also provides a survey of the current research projects in Europe for the evolution of PS wireless communications.

1) Long Term Evolution (LTE)

Technological advances in the commercial domain have led to top-of-the-line radio technologies able to achieve performance levels close to Shannon's bound. The state of the art of commercial wireless technology evolution is LTE mobile broadband technology, currently positioned to be the dominant technology in future commercial mobile networks. LTE is part of the GSM evolutionary path for mobile broadband, following EDGE, UMTS, HSPA and HSPA Evolution (HSPA+). The adoption of commercial mainstream LTE technology to deliver the increasingly data-intensive applications demanded by the PS agencies is gaining strong momentum among the PS community. In January 2011, the FCC in US adopted a Third Report and Order and Fourth Further Notice of Proposed Rulemaking (FNPRM) to support the build out of a nationwide broadband network based on LTE Release 8 [51]. In February 2012, the US Congress passed a legislation that has led to the creation of the First Responder Network Authority (FirstNet) charged with overseeing the deployment and operation of a nationwide LTE-based PS network. Also, in Europe, LTE technology is increasingly considered by the PS community as a possible broadband technology to be integrated with TETRA [52]. The adoption of LTE for mobile broadband PS is also backed by TETRA and Critical Communications Association (TCCA) (former TETRA Association) as presented in [53].

The adoption of LTE for Public Safety requires the specifications of services, which are present in the current digital PS wireless communication technologies but they are not usually defined in the commercial domain. A comparison of the services currently provided by TETRA and LTE is provided in [54], which also suggests that LTE may continue to be the choice for PS wireless data communication and the future solution for voice communication as well.

3GPP has started the standardization activity in three main areas, which are related to the PS domain:

1. Proximity services that identify mobiles in physical proximity and enable optimized communications between them. This is also called device-to-device communications. The work item in LTE Release 12 "Proximity-based Services Specification (ProSe)" SP-120883 [55] [55], currently focuses on the identification of use cases and technical requirement for communication between terminals, which are in proximity. The work item includes communication either with or without supervision from the network. The communication will consist of various media. Examples of media consist of conversational type communication (voice, video) or streaming (video) or data (messaging) or a combination of them.

2. Group call system enablers that support the fundamental requirement for efficient and dynamic group communications operations such as one-to-many calling and dispatcher working. The work

item in LTE Release 12 Group Communication System Enablers for LTE (GCSE_LTE) [56] shall specify the system enablers to the 3GPP system to support group communication over LTE for critical communications such as Public Safety.

3. Public Safety Broadband High Power User Equipment for Band 14 for Region 2 RP-120362 in LTE Release 11 [57]. This activity has the objective to specify high power user equipment for PPDR use for vehicle mounted terminals. This activity can facilitate the support of LTE in vehicular terminals.

These standardization activities can be used not only for the public safety domain but also other domains like transportation, utilities and government. An important issue is how to integrate the existing PS networks with the future LTE networks for PS to facilitate the seamless interworking and the migration between current and future PS networks.

LTE could become the wireless technology for Public Safety for the next generation but the following issues must be addressed:

a) There has been considerable investment in the current dedicated wireless communication frameworks in recent years. These networks will stay for the next 10-15 years. Future development of LTE technology must coexist and integrate with the existing infrastructures.

b) LTE is primarily a technology designed for the commercial market, which is orders of magnitude larger than the PS market. There is the risk that the PS community would not be able to influence the evolution of LTE standards.

A potential benefit of the adoption of LTE technology in the PS domain is that potential synergies between the future PS and commercial LTE infrastructures could be created. For example, networks resources could be shared. This is investigated more in detail in the FP7 HELP project as described in section IV.B.

2) Software Defined Radio

While LTE described in the previous section can address lack of broadband connectivity in the PS domain, other technologies can address lack of interoperability in a wireless communication scenario. In particular Software Defined Radio (SDR) technology has been evaluated to mitigate interoperability barriers in the military domain. The SDR concept was born in the military world with the US Military Joint Tactical Radio System (JTRS) program [58], which had the objective to specify a platform to interface and communicate with various military communication technologies. JTRS program has defined a Software Communication Architecture (SCA), to facilitate the development of software modules and SDR platforms and ultimately the portability of waveforms. A waveform is a software implementation of a specific wireless communication standard or Radio Access Technology

(RAT). An important goal would be to achieve portability of the waveform: the software modules, which implement a RAT, could be ported from a SDR platform to another with minimal or no changes in a similar way to PC applications, which can be installed on PC HW platform manufactured by different companies.

Figure 7 provides a potential architecture of a Software Defined Radio and its main elements. The Application Framework provides basic functions and libraries to support the applications and waveforms development and their Software portability. An example of software framework is the combination of SCA's CF (Software Communications Architecture Core Framework) and CORBA middleware. The waveform and the baseband processing represent collectively the implementation of a communication service (e.g., UMTS or TETRA). Finally, applications can be defined to support a specific operational or business context.

A recent survey on SDR technologies is provided in [59], where multi-standards SDR equipment is mentioned as a potential technology for the commercial and PS domain.

The application of SDR to the Public Safety domain has been investigated in [60] which investigated the benefits of software defined radio technology to support the resolution of natural disasters. In most cases, both public safety and military organizations (potentially of different nations) can participate to the disaster response. In such scenarios, the presence of interoperability barriers in the disaster area is a major challenge. SDR technology could be used to support different wireless communications technologies on the same radio platform. It is also necessary to define a common waveform to support the wireless backbone network. Aspects of interoperability are also extended to the three dimensions of platform, waveform, and information assurance
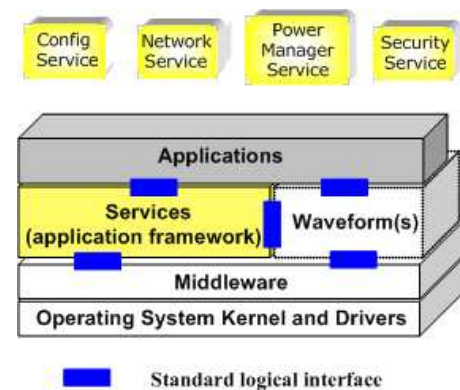

Figure 7 Example of SDR architecture

While SDR is a promising technology, some issues remain to be solved for the potential application of this technology in the public safety domain:

1. Military oriented solutions for SDR equipment are still relatively expensive for Public Safety

applications. Even if the price has decreased from the start of the JTRS program, it is still an order of magnitude higher than public safety vehicular terminals.

2. Waveform processing in SDR still require and consumer considerable computing resources and energy. While this may not be an issue for vehicular terminals, it could be an issue for handheld terminals.

3) Cognitive Radio

In ETSI [61], Cognitive Radio is defined as "radio, which has the following capabilities: to obtain the knowledge of radio operational environment and established policies and to monitor usage patterns and *users' needs; to dynamically and autonomously adjust its* operational parameters and protocols".

The design and deployment of have been investigated in a number of papers and research studies starting from the paper of Joseph Mitola [62].

It is usually recognized that CRs should provide the following functions:

- Determine which portions of the spectrum are available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing)
- Select the best available channel (spectrum management) for communication
- Coordinate access to this channel with other users (spectrum sharing)
- Vacate the channel when a licensed user is detected (spectrum mobility)

These functions and their relationships are dependent on each other as described in Figure 8. For example: spectrum mobility can alert the spectrum sensing function on detected changes in the spectrum environment. Acting on the alert, the spectrum sensing function can collect again the knowledge of the spectrum environment and provide it to the spectrum management function to re-plan the allocation of spectrum bands. These functions may be important to support the flexibility needed in disaster management, when PS organizations have to face unpredictable events or a difficult environment where fixed communication infrastructures may be degraded and destroyed.

The application of CR in the PS domain has been investigated in various papers.

In [63], the authors identify the reasons why cognitive radio could be a successful solution for the lack of available spectrum bands for the PS domain. The paper suggests that policy-based cognitive radio systems operated on a cooperative, shared basis could lower costs of use and aid coordination for PS responders in disaster response or emergency crisis.

In [64], the authors describe how awareness, learning and intelligence features of cognitive radios can support the operation capabilities of public safety and emergency case communications. One specific aspect is the development of applications that will lead to communicate, locate and reach victims who are stuck in disaster areas, underground (e.g. underground mine explosions) or behind obstacles.
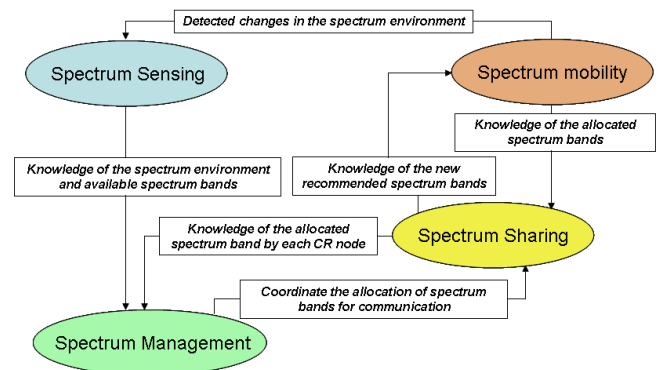

Figure 8 cognitive radio functions

Finally, in the long run, the use of CR's with spectrum sharing capability is believed by many regulators to be the answer for the spectrum congestion problem [65]. A flexible spectrum framework is expected to pave the way for "policy-based" adaptive-radio regulatory framework. In early implementations in licensed bands, a static allocation of spectrum (for primary usage) could be complemented by the opportunistic use of the unused spectrum in an instant-by-instant basis in a manner that limits interference to primary users. In this approach the CR monitors the spectrum in which it wants to transmit, looks for inactivity in time and frequency and transmits without interference to primary users.

While CR is a promising technology, some issues remain to be solved for the potential application of this technology in the public safety domain:

1. Specifications for the use of CR technology in the PS must be defined by spectrum regulators. While the "White Space" approach has received considerable attention by spectrum regulators, CR in PS domain is still in the research/investigation phase, even if there have been already initiatives in this direction: in USA, the FCC has recently (December 2012) published a communication [66] recommending spectrum sharing and small cell use in the 3.5 GHz Band, where PS organizations could also use the spectrum on a shared basis. In September 2012, the European Commission has published a communication promoting the shared use of radio spectrum resources, [67] where PPDR broadband public protection and

disaster relief (PPDR) applications are explicitly mentioned.

2. PS organizations have strong requirements for timely access to networks resources and security as described in section II.C. There are not many studies, which investigated the performance of CR networks for PS domain. This is a research topic where additional work is needed.

B. Status of security research in Europe

Current security challenges such as global terrorism and environmental disasters have increased public awareness and political support to enhance the capability and efficiency of PS organizations. In Europe, this is an opportunity forced also by the progress of the European integration which is a driving force for a closer cooperation among PS organizations across Europe. As a consequence, there is increasing support at the political level to support research activities to improve the communication capabilities of PS responders.

The European Commission, through the Framework Programme 7 (FP7) has funded various projects in the area of wireless PS communications. Only the most recent projects are identified in this paper:

- The FP7 HELP project [68] proposed a solution framework targeted to create and exploit synergies of composite radio systems encompassing commercial and dedicated PS technologies and networks. The proposed solution framework is based on the adoption of LTE technology for PS domain and it strengthens the role and commitment of commercial wireless infrastructures in the provision of PS communications. The reason is that a single dedicated infrastructure may not provide adequate services and capacity in case of a major crisis or large natural disaster. The solution framework is based on the exploitation of network sharing and spectrum sharing principles and the adoption of Long Term Evolution (LTE) technology for mobile broadband PS applications. Network sharing refers to the shared use of a network, or a part of it, by multiple users. Different types of services for different user organisations may be provided by one or several network operators, which may have a different degree of control over the shared network resources. Spectrum sharing is a term usually used to describe co-existence with an incumbent radio-communications application (-s) within the same frequency band as proposed for new application(s).

- The EULER project (EUropean Software Defined radio for wireless in joint security operations) [69] applied SDR technology to mitigate the lack of interoperability in joint military and PS operational scenarios. The technical solution, adopted by the EULER project is based on SDR and the EULER Waveform (EWF) to provide a broadband wireless backbone, which can be used to transport data among heterogeneous networks and end-users. Security aspects were also addressed. EULER did not consider LTE standards and technologies, but the concept of SDR fits very well with the need for a multi-mode platform, which can communicate using different wireless communication standards.

- The DITSEF project [70] (Digital and Innovative Technologies for Security and Efficiency of First responder operations) will provide a self-organising, robust ad-hoc communications networks with location information, which can be used in critical infrastructures and indoor environments where lack of radio propagation usually hamper the functioning of conventional communication systems. From this point of view, DITSEF is an extension of the concepts already described in this paper to indoor environments which were not previously addressed.

- The INFRA project [71] (Innovative and Novel First Responders Application) project has the objective to research and develop novel technologies for personal digital support systems, as part of an integral and secure emergency management system to support First Responders (FR) in crises occurring in Critical Infrastructures (CI) under all circumstances. In this context, the results of INFRA can be integrated with the results of the other projects.

Beyond the single FP7 projects, the European Commission DG ENTERPRISE has strongly supported an integrated policy for the security industry at European level. As described in [72], the Commission considers that the development of 'hybrid standards', i.e. standards that apply both to civil security and defence technologies, should be actively pursued in areas where technologies are the same and application areas are very similar. In this context, a mandate for reconfigurable radio systems technologies is in preparation. The mandate addresses commercial, PS and military domains, with the effort to identify synergies when feasible. The new standardization mandate was the main focus of the workshop hosted in the facilities of the Joint Research Centre (JRC) of the European Commission in Ispra, Italy on the 17th and 18th of November 2011. The workshop was organized by EC DG ENTR, European Defence Agency (EDA) and EC DG JRC to identify the key drivers, roadmap and actions for the standardization mandate on the basis of the input of the stakeholders (around 60 participants). In this regard, the workshop was extremely useful to identify the main inputs for the commercial, PS and military markets.

On a similar topic, but more specifically targeted to the radio frequency spectrum management, DG INFSO (now

DG CONNECT) and other DGs (DG ENTR, DG ECHO) organized a workshop on the 30th of March 2011 on "The future of PPDR services in Europe". It was attended by 90 participants representing national administrations and governmental organisations responsible for PS tasks, spectrum regulators, equipment manufacturers and telecom operators, as well as a representative of the European Parliament. A report is available at [73].

V. CONCLUSIONS

This paper identified the different operational contexts, functions and requirements of PS organizations and described the different wireless communication technologies used by PS organizations in emergency response and the technology standards and regulatory frameworks governing PS organizations. The potential evolution of communication technologies in the PS domain was also discussed, noting some current technological developments. This paper serves as a comprehensive survey of the wireless communication technologies in emergency response.

While existing wireless narrowband communication technologies like TETRA, APCO25 and TETRAPOL are able to support the operational requirements of PS officers in the field for voice communication and limited data connectivity, there are serious limitations for the provision of broadband connectivity and applications, which are already available in the commercial world. Furthermore the fragmentation of PS wireless communication systems can create problems of interoperability, which can negatively impact the resolution of natural disasters or emergency crisis. This paper has described potential technologies, which could address these gaps. Depending on the political support for the public safety domain these technologies could be deployed in the PS market and open the way for greater synergies with the commercial domain.

Finally, it is worth considering that while the literature suggests that the PS sector is a niche market; if we reflect on the number of major emergencies over the last ten or more years, including terrorist attacks and environmental catastrophes, then we have to recognize the relevance of these technologies and the importance of the work of PS organizations in modern society.

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