Adaptive and Cognitive Communication Architecture for Next-Generation PPDR Systems

Ozgur Ergul, Ghalib A. Shah, Berk Canberk, and Ozgur B. Akan

The authors examine the state of the art in areas related to communication in PPDR systems, and discuss the open research issues for each topic. Then they propose a novel architecture that meets the aforementioned requirements and relies on a novel device called an ICG.

ABSTRACT

In light of recent natural catastrophes and terrorist activities, it has become evident that new architectural approaches are needed for next generation public protection and disaster relief networks. These architectures should be adaptable to the conditions at the event site and resilient enough to operate under adverse conditions in an emergency. Furthermore, they should enable rapid gathering of crucial event data and its delivery to the responder units at the site as well as the command and control center that is off-site. In this article, we first examine the state of the art in areas related to communication in PPDR systems, and discuss the open research issues for each topic. Then we propose a novel architecture that meets the aforementioned requirements and relies on a novel device called an ICG. An ICG enables flexible use of the spectrum and facilitates data gathering from all lower-tier devices and relays this data to relevant units through the higher-tier public or commercial backhaul networks. Finally, we provide some results that justify the need for these devices in emergency scenarios.

INTRODUCTION

When responding to emergency situations, the quality and sustainability of communication have a great impact on the performance of first responders. Recent natural catastrophes (e.g., Hurricane Katrina) and terrorist activities (e.g., the London metro bombings) revealed that even the most recent TETRA/TERAPOL systems have inadequacies.

The current public protection and disaster relief (PPDR) networks provide feature-rich voice-centric services, but they offer a very limited range of data services for imaging, video, and data files. Recently, Tetra Release 2, Tetra Enhanced Data Services (TEDS), was introduced. Although some efforts have been devoted to upgrading the existing standards with wideband data capabilities, the development toward an enhanced mobile broadband solution for public safety lags far behind commercial mobile broadband wireless networks [1]. Moreover, today's urgently missing requirement is interoperability, not only between different services, but also within the same service if different systems are in operation between regions [2]. Furthermore, TETRA/TETRAPOL networks have a cell-based central structure, and failure in a base station (BS) leads to large coverage loss and possibly network partitioning.

To address these inadequacies, there has been an increasing amount of work in the literature on network resilience and PPDR networks. Our aim in this article is two-fold. We first classify and examine the previous work in the literature, discussing open research venues for each sub-topic. Then we focus on research related to data retrieval during and after an emergency, and introduce a novel multi-tier cognitive communication architecture for adaptive and sustainable wireless communication required in PPDR operations.

So far, the existing works on communication in PPDR systems have only partially addressed the problem of providing uninterrupted/sustainable communication. Some propose a dedicated network for public safety operation such as TETRA/TETRAPOL, while others rely on the existing commercial networks [3]. Although some cognitive radio (CR) architectures [4] are also proposed to counteract the failure of the existing networks, all these efforts are made in a non-collaborative manner, and there is a need to intelligently integrate them and address different issues in a focused way.

PREVIOUS WORK

One of the greatest problems in current networks is the lack of resilience. The research on network resilience can broadly be divided into two, as research aiming pre- and post-emergency.

RESEARCH ON PRE-DISASTER IMPROVEMENTS

Most of the research in the literature on network resilience, specifically in PPDR networks, may be included among improvements that can be made before an emergency. These mainly include:

- Resilience analysis
- Resilient network design
  - Resilient backhaul network design
  - Resilient access network design

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- Developing resilient network layers or modifying existing network layers to introduce resilience

Resilience Analysis: Resilience analysis research includes finding meaningful metrics to analyze networks in terms of failure types, and developing algorithms that can generate resilient network topologies. Moreover, conventional performance metrics are not suitable for mission-critical networks [5]. With these metrics, high-probability events dominate their effect on the performance measures. However, in mission-critical networks, certain events with rare occurrences may have dramatic importance. For example, if link sustainability is taken as an important metric, the resulting design may prioritize finding channels that retain desirable conditions. However, in the case of a terrorist attack, an adaptive jammer that looks for good channels to jam may render these solutions highly ineffective.

The European Network and Information Security Agency (ENISA) issued a report on resilience metrics [6]. The report does not propose new metrics but rather lays out an overview of previous work on the subject. It is pointed out that measuring the effectiveness of current resilience policies is challenging, and the discipline is still in its early stages.

No consensus is developed on the identification of metrics and standards for measuring resilience. The United Nations Development Program (UNDP) recently conducted a survey of the resilience measures taken across the world [7]. The report indicates that resilience has various elements (well being, vulnerability, etc.), levels (e.g., inputs, impacts), and dimensions (technical, economic, etc.). Furthermore, measurements may be tailored to context (e.g., the Country Disaster Resilience Index for coastal communities). The conclusion of the report is that the resilience metrics and measurements should cover as many of these elements, dimensions, and so on as possible.

Resilient Network Design: Resilient network design research has mostly been on backhaul networks. Standards such as IEEE 802.17 on resilient packet ring (RPR) address resilience directly. Amendments to existing standards, such as IEEE 802.3ah (Ethernet passive optical networks) and recommendations, such as International Telecommunication Union Telecommunication Standardization Sector (ITU-T) G.984 (gigabit passive optical networks) help in developing backhaul networks that remain operational in case of power shortages. These approaches take advantage of the ability to function without electrically powered switching components.

Research on this front mostly focuses on ring or mesh topologies that introduce redundancy to obtain fault tolerance [8]. New approaches that use recently emerging network types are needed. For example, vehicle-to-roadside (V2R) communication is a recent hot topic. In the case of backhaul network failures, these networks may be utilized. However, they are generally designed in a linear fashion and lack redundancy, and thus fault tolerance. Also, handover algorithms for V2R are straightforward due to the simple network structure. Introducing resilience to such recently developing networks through either network design (e.g., mesh V2R networks) or algorithm design (e.g., resilient handover algorithms) to exploit them in an emergency scenario is an open research area.

Software defined networking (SDN) is a new paradigm that simplifies network management by decoupling the decision making system on traffic forwarding (control plane) from the actual underlying system that does the forwarding (data plane). Due to this abstraction, SDN provides a very convenient means for traffic management in case of a disaster [9]. There is a minimal amount of work in the literature on using SDN to design disaster-resilient backhaul networks. Algorithms that can rapidly adapt to new conditions in the case of component failures and configuration changes, which may occur frequently after a disaster, are needed. Analysis and efficient methods that consider mapping of virtual resources to physical components are also among the open research issues.

When a disaster strikes, wired backhaul networks may fail due to wire cuts. Wireless backhaul networks provide a promising alternative. Generally, directional antennas are used in wireless backhaul networks to meet the high performance required. Since the number of directional antennas per unit is limited, node degree is limited. However, to increase resilience and introduce fault tolerance, high node degree is desired. New research efforts that address the trade-off between node degree, network performance, and cost are needed. Another open issue is designing resilient wireless backhaul networks based on the results of these trade-off analyses.

Compared to the research on resilience of backhaul networks, the effort on designing resilient access networks is limited. Access networks may provide invaluable data for first responder units after a disaster. Consider an example case where an operational wireless access point (AP) in a collapsed building can communicate with a wearable health monitoring device in the wireless personal area network (WPAN) of a patient. By accessing the AP, first responder units may gather vital data for their rescue operations.

There are many open research venues on this topic. To name a couple, methods that make use of power line communications (PLC) are needed. Recently, PLC is being considered as part of home digital networks [10]. With proper design, a PLC network with components that have backup batteries may still be partly operational after a disaster, even with occasional power line cuts. Another important alternative is designing resilient femto/picocell home area networks (HANs). Resilient network designs that make use of these new and emerging access networks are needed.

Resilient Network Layers: Algorithms that are developed for various network levels, such as routing algorithms, congestion control algorithms, and network coding algorithms, must be reconsidered to increase traffic flow resilience in case of component failures. Most of the research on this topic is on developing countermeasures for malicious attacks [11]. However, outages due to disaster cases are different. There is a limited amount of work in the literature, such as [12], where a cognitive routing protocol that takes quality of service (QoS) into account is proposed.

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Category	Research area	Open issue
Pre-disaster improvements	Resilience analysis	Metrics suitable for mission-critical networks
		Resilience analysis for mission-critical networks
	Resilient network design	Resilient network architectures for both backhaul and access networks
		Introducing resilience to emerging networks (e.g., V2R, CPL, HAN)
		Resilient traffic forwarding algorithms (SDN)
		Resilient network and source coding
		Resilience when mapping virtual resources to physical components
		Resilient network structures for wireless backhaul networks
	Resilient network layers	Spectrum awareness and OSA capability for existing devices
		Modifications to network layers for traffic flow resilience
Post-disaster limprovements	Through-the-wall inspection	UWB for through-the-wall vision
		Inspection of interference of UWB on NB devices
	Operational device ID	Detection algorithms for operational wireless devices in event areas
	Resilient data fusion and routing	Combined use of directional antennas and OSA
		Resilient data fusion
		Spectrum as an additional dimension in routing via OSA

Table 1. Categorization of studies on PPDR.

Opportunistic spectrum access (OSA) provided by CR may prove to be of great value for establishing communications in case of a disaster. Research on this front is very limited. Routing algorithms that consider spectrum availability, sensing algorithms that can search, identify, and communicate with operational access network devices, and algorithms that consider directional transmission with spectrum availability are some of the open research areas on this topic.

Research on Post-Disaster Improvements

Research on work that must be performed after a disaster mainly consist of means of data retrieval from the emergency area, and forwarding this data to first responder units and their command and control centers. These can be broadly categorized as:

- Through-the-wall inspection
- Operational device identification
- Resilient data fusion and routing

Through-the-Wall Detection: Firefighters and first responders use through-the-wall detection technologies to locate people in collapsed or burning buildings. The most dominant research area is ultra wideband (UWB) [13]. However, since UWB uses a very large bandwidth, its impact on wireless communication in the event area must be analyzed. It has been reported that even though interference from a single UWB device has a negligible effect on narrowband (NB) devices, if the NB receiver is closer to the UWB transmitter than to the NB transmitter, this may cause very low signal-to-interference ratio (SIR) and performance degradation in the NB link [14].

Operational Device Identification: Another important issue is to identify operational devices inside the event area. These devices can provide invaluable information to first responder units. They may be under collapsed concrete or in distant locations that first responders cannot move into due to the nature of the disaster (radiation, fire, etc.). To increase the chance of identifying and communicating with operational access network devices, intelligent means of using directional antennas and fast sensing algorithms that can scan the spectrum bands of these devices are essential. There has been some work on direction of arrival (DoA) estimation to increase the performance of directional antennas [15]. However, algorithms that coordinate scanning of bands in conjunction with DoA to discover operational devices are needed, considering that these operational devices may use a variety of access technologies (IEEE 802.15, GSM, 3G, etc.).

The radiation patterns of directional antennas differ with frequency. Methods that use CR capabilities with directional wireless communication can increase performance. These methods should also consider fading since fading varies with the communication frequency. Therefore, more resilient and efficient communication may be possible with novel algorithms that take into account all of the aforementioned factors.

Resilient Data Fusion and Routing: When operational wireless devices are found using the means mentioned above, algorithms to retrieve data efficiently and rapidly is essential. Cognitive radio sensor networks are a relatively recent paradigm [16] and can be very useful in a PPDR network architecture. A CR network can also be used to restore functionality to partially destroyed networks by providing connectivity through alternative bands as proposed in [17]. Such novel resilient data delivery and data aggregation algorithms, and restorative routing algorithms that consider spectrum availability must be developed.

We present a summary of the open issues in Table 1 for each research area. One of the overlooked capabilities in PPDR architecture is the capability to extract data from the event area, from either still functional devices in the area or devices deployed by the first responder units after the event. In the following section, we present a new adaptive and cognitive PPDR architecture that has the features and structure to cover this shortcoming.

Adaptive and Cognitive Communication Architecture for PPDR

Post-disaster improvements have attracted less interest from the research community compared to pre-disaster improvements. The limited existing effort is generally focused on one aspect such as the information and communication technology (ICT) infrastructure for PPDR vehicles and satellite communication. In this section, we lay out a broader proposal for a new PPDR network architecture that aims to gather data from the event area in case of an emergency and forward this crucial information to command units. First, we list the challenges that must be overcome by such architecture.

CHALLENGES

Spectrum Usage: The fundamental challenge in PPDR systems is to specify the part of spectrum for exclusive use of PPDR communication. However, with new applications such as real-time video from drones and through-the-wall imaging, the demand for bandwidth in future first responder networks will be exceptionally high, and exclusive access to the spectrum may not be sufficient since only a limited amount of bandwidth can be spared for any one service

Interoperability: In disaster scenarios, various national and international organizations perform rescue operations to cover the large incident region. This requires interoperability of devices and equipment.

Self-Organization: In order to help emergency personnel concentrate on their tasks, an incident area network should be deployed quickly with little human maintenance. Therefore, devices must be capable of self-organizing into a network.

Reliability: Reliability is required for data to be consistently and continuously transported to the central command station or data collection points. Also, first responders' connections among themselves and the command center should be reliable.

Scalability: This refers to the ability of a system to support a large number of parameters without impacting performance. These parameters include number of nodes, traffic load, and mobility aspects. Limited processing and storage capacities of radio devices are also a concern.

THE NETWORK ARCHITECTURE

We propose a novel multi-tier cognitive communication architecture that can overcome these challenges. The required resilience and adaptation are provided with the concept of intelligent cognitive gateways (ICGs). An ICG is a gateway with multiple interfaces to interact with both various low-level devices, including sensor nodes, RFID readers, WiFi routers, and so on, and high-level devices, such as commercial and backbone network devices. ICGs provide means for OSA through their cognitive radio interface. They can be manufactured in various forms such as mobile ICGs and ICGs with the capability of passive communications. The details of the three-tiered architecture are as follows.

Low-Tier Application Network: The low tier consists of wireless sensor network (WSN) nodes composed of any kind of sensing devices, remote health monitoring, telemetry, and voice phones. The low-tier elements are usually low-power devices with short-range communication capabilities.

The potential applications commonly realized in PPDR systems deploy a variety of low-tier devices used for day-to-day operations, as well as on-scene mobile devices. For example, a remote healthcare monitoring application can deploy ECG, asthma (nanotube asthma sensor), swine flu, and diabetes sensors (glucose sensor, etc.) in the low tier. Several of these low-tier elements are organized in one unit and can form a network nucleus interfacing to the middle tier by one gateway/port only.

An example of the network nucleus could be an RFID reader fetching information from a large number of tags. Thus, a low-tier network is analogous to a WSN that builds ad hoc auto-configuring architecture based on a short-range transmission network. Data collected by these devices are sent to a nearby ICG directly or via multihop routing through neighboring nodes. Therefore, ICG integrates the most widely used low-power wireless interfaces such as IEEE 802.15.4. Additionally, battery-less devices may also be used. These devices do not communicate actively. They have a passive radio interface that can modulate reflected waves. This enables mobile ICGs to move into the event area and fetch information from these passive sensing devices by sending radio waves to them.

Middle-Tier PPDR Infrastructure: ICGs form the middle tier of the architecture and enhance the existing PPDR infrastructure. They provide close-up connectivity to lower-tier devices in order to access a backhaul network. These ICG nodes are not only deployed for day-to-day routine operations of the evolving PPDR applications, but also allow self-configured ad hoc extension to the infrastructure in incident areas. ICGs are equipped with intelligent CR capability that can tune into any of the communication bands of the lower-tier devices, recognize and authenticate nodes, and provide communication interface to/from application networks. Each ICG forms a cluster with its lower-tier surrounding devices.

Established standards for CR, such as IEEE 802.22 and IEEE 802.11af, have certain problems when used in a first responder network. 802.22 is a centralized approach that relies on a BS. Basing the whole architecture on a BS that may not be operational is a problem. On the other hand, 802.11af requires connection to a geolocation database (GDB) to query available bands. Such connection may not be available in an event area. However, first responders may keep copies of these databases and bring them along to be used in the emergency area. Therefore, IEEE 802.11af is better suited for our architecture.

High-Tier Access Network: The third tier is formed by the existing radio networks used for surveillance or monitoring such as TETRA and TETRAPOL or commercial GSM/LTE networks, satellite networks, or even WiFi hotspots, as shown in Fig. 1. For backhaul access, ICGs forward data through other ICGs until contact with one of these backhaul networks can be established and then exploit these existing infrastructures.

The deployment of ICGs mainly includes the establishment of static ICG sites to provide coverage in all the possible regions where the PPDR organizations may operate.

According to the capacity requirements, the

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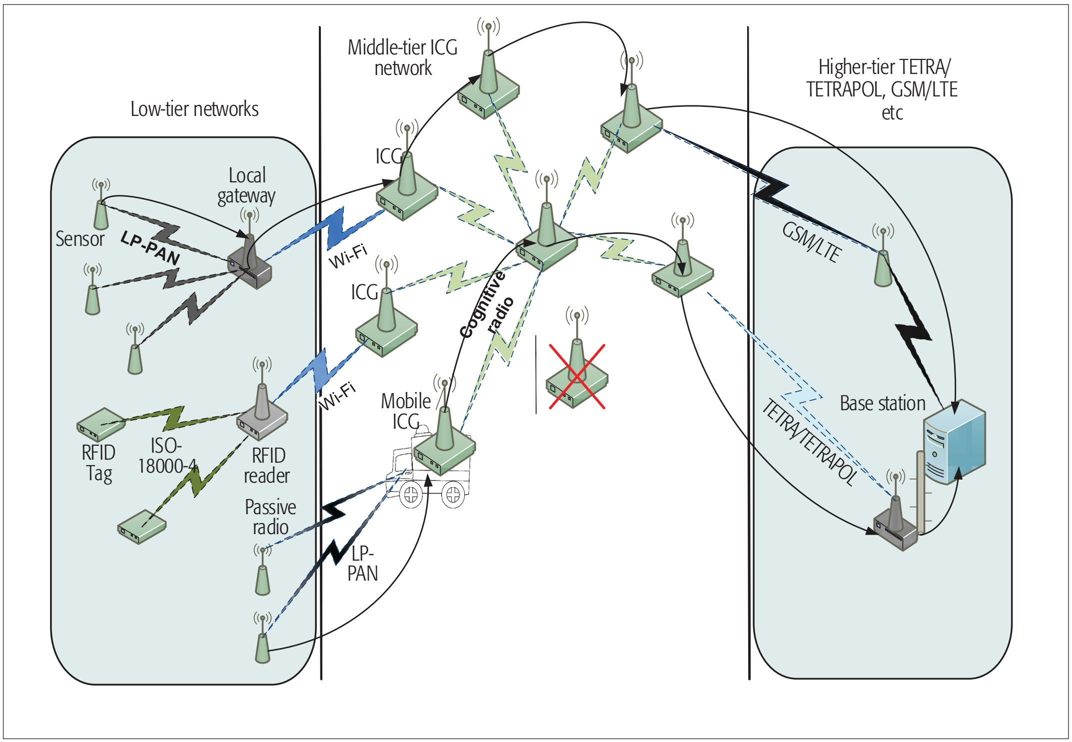


Figure 1. Proposed architecture for future PPDR Infrastructure.

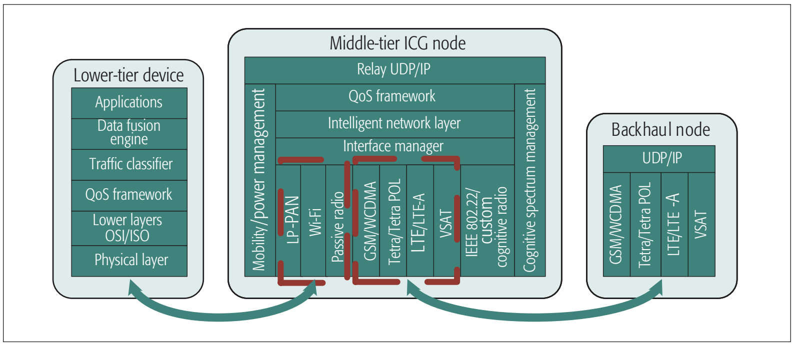


Figure 2. Communication protocol stack of the architecture.

deployment also ensures that the ICG network has sufficient connectivity with the backhaul networks connecting to PPDR remote stations. Moreover, the self-configuration property of the communication protocols developed for ICG networks allow mobile ICGs to join the network spontaneously to overcome the possible failures of existing nodes or extend the coverage area in no time. Thus, the ICG network aims to enhance the existing infrastructure of public (TETRA), commercial (LTE), and satellite networks. Moreover, ICGs also facilitate PPDR applications by supporting multiple fixed spectrum interfaces in addition to OSA for ubiquitous communication. Furthermore, the ability to self-configure and adaptively change communication parameters provides robustness and sustainability, which are much needed in disaster relief scenarios.

PPDR Communication Framework

Figure 2 demonstrates the system-level approach to designing communication protocols at different tiers of the proposed PPDR architecture. Data from different applications running on a PPDR network is classified using a traffic classifier layer according to the priority of the application or a particular scenario to achieve minimum time of delivery of an event from the network layer, where the event has been detected, to the decision point. An early warning system is based on micro-fusion of data supplied by local sensing element and traffic classifier output. A QoS framework based on the communication requirements of PPDR data maps the classified traffic to different traffic queues for transmission and ensures that the required QoS is provided to each traffic class.

The network layer and other lower layers of the International Standards Organization Open-Systems Internconnection (ISO/OSI) provide an addressing mechanism, and error correction and link layer functionality, and are responsible for routing data to a BS using appropriate ICGs. SDN can be used here. However, SDN has a centralized approach [18], whereas an ICG network has an ad hoc structure. Moreover, such centralized approaches have single points of failure. Therefore, SDN is more suitable for a higher layer, and may especially prove valuable for interoperability by controlling and coordinating the flows of different first responder units.

A middle-tier-forming PPDR infrastructure is built by the deployment of a number of ICGs in pre-disaster arrangement as well as on-scene deployment of ICGs. These ICGs implement self-configuration protocol to enable flexible and resilient PPDR architecture. They also implement ad hoc routing protocol to dynamically determine the route according to the availability of the infrastructure. Essentially, they are relay nodes that forward application data from lower tiers to the application BS. Since the proposed

Architecture	Proposed architecture	TEDS	LTE-based	Satellite-based [3]	CR-based [4]
Interoperability	Yes (multi-interface)	No (only TETRA R2)	Only LTE devices	WiFi and satellite (L, S, Ku, Ka Bands)	No
Expansion	Yes (due to mobile ad hoc ICG nodes)	Limited	Not possible	Yes (due to vehicle communication gateway nodes)	Yes
Anti-jamming	Cognitive spectrum provides more resilience against jamming or attack	Fixed spectrum, jammed bands cannot be restored	Fixed spectrum, jammed bands cannot be restored	Fixed spectrum, jammed bands cannot be restored	Yes
Recovery	Easy recovery in disaster (multihop and mesh connectivity)	Might be unavailable in a disaster	Might be unavailable in a disaster	Limited (no multihop)	Might be unavailable in a disaster
Deployment	Infrastructure/ad hoc	Infrastructure	Infrastructure	Infrastructure/ ad hoc	Infrastructure/ ad hoc
Broadband	Yes	Wideband (up to 450 kb/s)	Yes	Yes	No (only voice)

Table 2. Comparison of existing work with our architecture.

architecture is an enhancement to the existing PPDR infrastructure, it integrates existing commercial and public wireless networks into our architecture by adding an interface to the ICG. Therefore, it enables the pre-installed communication infrastructure to be exploited using UDP or TCP/IP to access the application BS. While communication between the ICGs is performed over a CR interface, this makes the ICG middle tier network spectrum efficient and resilient. Its functions are divided into the following layers:

- The relay layer acts as a relay and builds the data to an IP packet for transmission to a higher tier.
- The QoS framework implements the services that include mapping the lower-tier QoS functions to higher-tier QoS functions, prioritizing interfaces, and so on.
- The intelligent network layer performs the task of finding a route and an appropriate interface to send data to the BS. This may involve coordination with other ICGs.
- The interface manager maintains and monitors the status of each interface and acts as a single access point to higher layer. It also shields all the underlying interfaces' complexity to simplify the design of higher layers.

COMPARISON OF ARCHITECTURES

In this section, we aim to present a comparison of the proposed architecture with other PPDR architectures in the literature. We investigate six criteria that we believe are important for future PPDR networks:

- Interoperability indicates that the architecture supports multiple network interfaces of various first responder units.
- Expansion is the ability to increase coverage on demand.
- Anti-jamming is required for terrorist attacks.
- Recovery is the ability to cover for failed units in the architecture.
- Deployment indicates whether the architecture is infrastructure-based or ad hoc.

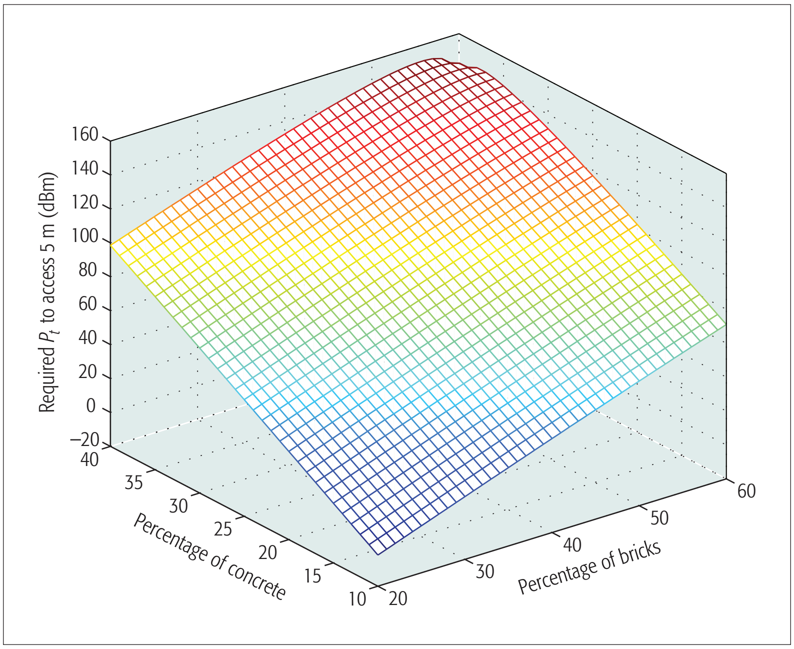
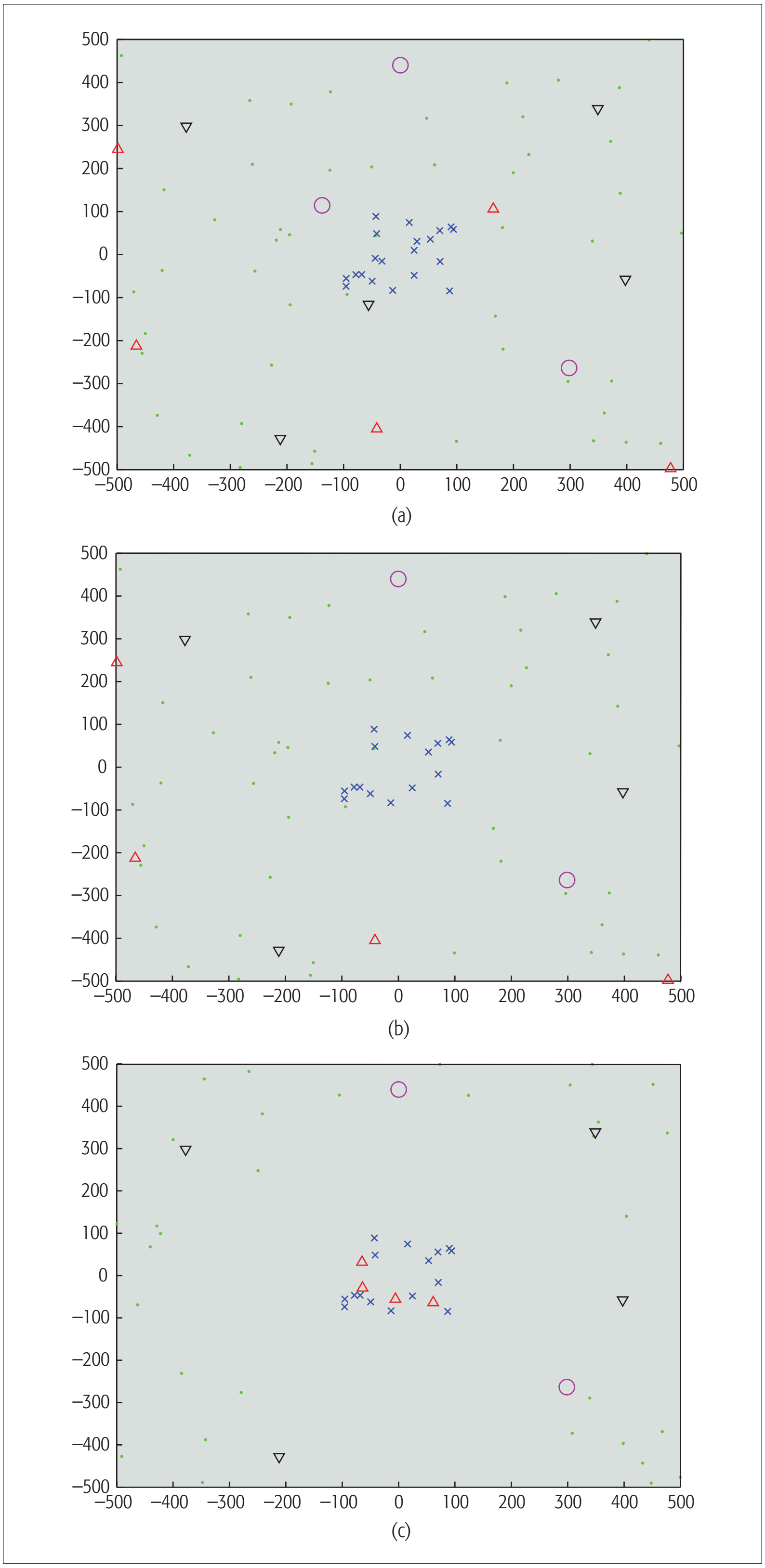


Figure 3. Power required to transmit to 5 m for various material percentages.

- Broadband capability is the final criterion in which we are interested.

We present comparison of our architecture with four other architectures, TETRA Enhanced Data Services (TEDS), the LTE-based solution proposed in [1], the satellite-based architecture in [3], and the CR-capable solution in [4].

As summarized in Table 2, our solution covers the widest range of features. The new TETRA network architecture has problems mainly due to its strict infrastructure-based architecture. It lacks important capabilities such as data forwarding and dynamic spectrum access. Furthermore, despite the improvements, it still has insufficient bandwidth for future PPDR networks, which have high bandwidth demands (e.g., for real-time video). The LTE-based approach suffers from similar inadequacies except for bandwidth. The architecture proposed in [3] offers some flexibility by use of mobile access points. However, it cannot offer anti-jamming since it does not have CR capability, and only offers limited recovery since it does not support multihop communication. The CR-based solution does not support data links and, like the others, does not have interoperability support.



(a)

(b)

(c)

Figure 4. Sample positions for simulation elements.

To highlight the capabilities of ICG, we analyze a hypothetical case. ICGs are deployed in a building before a disaster. We present a simple analysis of the communication area inside the rubble that can be covered by ICGs. We take the path loss as 7 dB and 4 dB for concrete and brick, respectively, for a thickness of 0.1 m.

We have evaluated path loss of these materials and found it to be linear in the log scale. These results are in line with those in the literature (e.g., [19]). We assume a receiver sensitivity of –110 dBm, and transmitter and receiver antenna gains of 30 dBi. Transmission power of 50 dBm is assumed to be used in an emergency situation. This allows for a total attenuation of 190 dB. We realize that this power value is much higher than the allowed 2 W effective isotropic radiated power (EIRP) in Europe and 4 W EIRP in the United States. However, ICGs will only use this high transmission power mode for emergency rescue operations for a very short time to collect data from the event area. Therefore, we think this is a reasonable assumption.

In Fig. 3, we show the amount of power needed to transmit successfully over a 5 m distance for various percentages of concrete and brick in the rubble. For a high number of cases, ICGs can transmit data when they are 5 m deep in rubble.

SIMULATION RESULTS

In this section, we provide the results of the simulations we performed to demonstrate the effectiveness of our architecture. We assume a disaster scenario where a certain emergency situation (fire, bombing, etc.) occurs in the middle of the simulation area, which is taken to be 500 m × 500 m. People, sensors, ICGs, and primary users (PUs) are located randomly according to a Poisson point process within the area. Since we are only interested in the sensors located in the event area, we focus on sensors within 100 m of the event.

To compare the effectiveness of ICG, we also place an equal number of non-mobile WiFi access points (APs) inside the area. We believe five APs inside a 500 m × 500 m area is a reasonable assumption. We choose WiFi for comparison, because centralized systems such as cellular have the problem of single points of failure, which is critical in disaster scenarios. We assume a channel bandwidth of 20 MHz for APs, as supported by most IEEE 802.11 variants. Assuming ICGs use TV white space, we take 6 MHz as the channel bandwidth for ICGs. Since nowadays most TV users are cable subscribers, the number of TV users that use over-the-air antennas is small. Therefore, we assume three PUs.

After the event, some of the devices are destroyed with probabilities inversely proportional to their distance to the event. Furthermore, people and ICGs start to move. We assume the "gravitational" mobility model proposed in [20], that is, people move away from the event area with velocities inversely proportional to their distance to the event, and ICGs move toward the event area with velocities proportional to the square of the distance to the event.

We compare the throughput of data gathered from the sensors by ICGs and APs by repeating the same scenario for both cases. We run the simulation 1000 times with different random placements. For each placement, we assume PU existence probabilities (probability of a PU being active) from 0.1 to 0.9.

In Fig. 4, we show sample random location distributions before the event, right after the event and at simulation end (i.e., 200 s after the event), respectively. By comparing these figures, we see that some of the equipment is destroyed in the event. Also, people have moved away from the event area and ICGs have moved closer by the end of 200 s.

We present the throughput obtained by both ICGs and APs as time passes in Fig. 5. ICGs provide higher throughput even though their channel bandwidth is considerably lower (6 MHz vs. 20 MHz). As time progresses, people move away from the area, reducing both the number of users served by APs and the interference on APs. Therefore, AP throughput increases with time. However, ICG throughput increases more rapidly, since ICGs can get closer to the sensors and further increase their signal-to-interference-plus-noise ratio. The wider deviation in ICG throughput is due to different PU existence probabilities.

The effect of PU existence probability is presented in Fig. 6. We see that ICGs perform better up to PU existence probability of 0.85. This shows that our proposed architecture enables higher throughput for the majority of cases due to its CR and mobility capabilities.

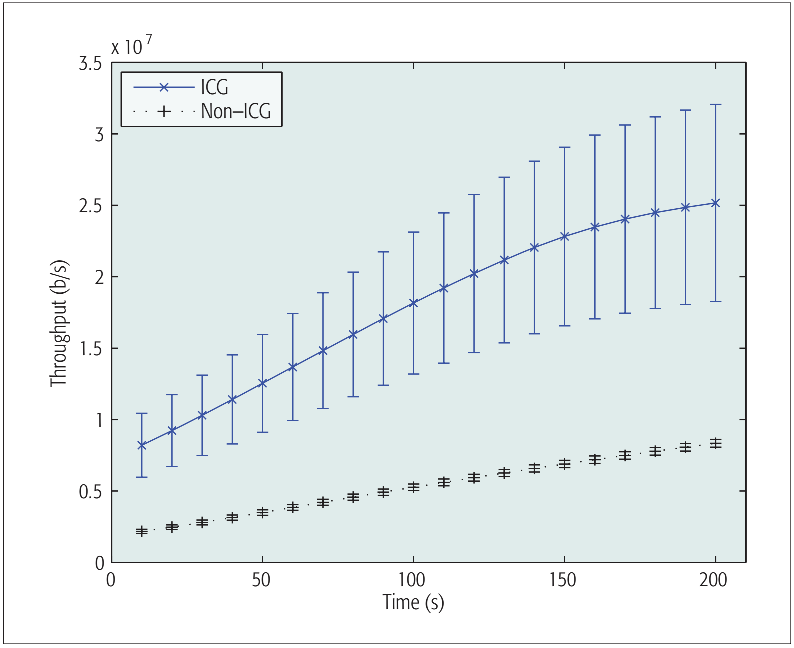


Figure 5. Throughput vs. time.

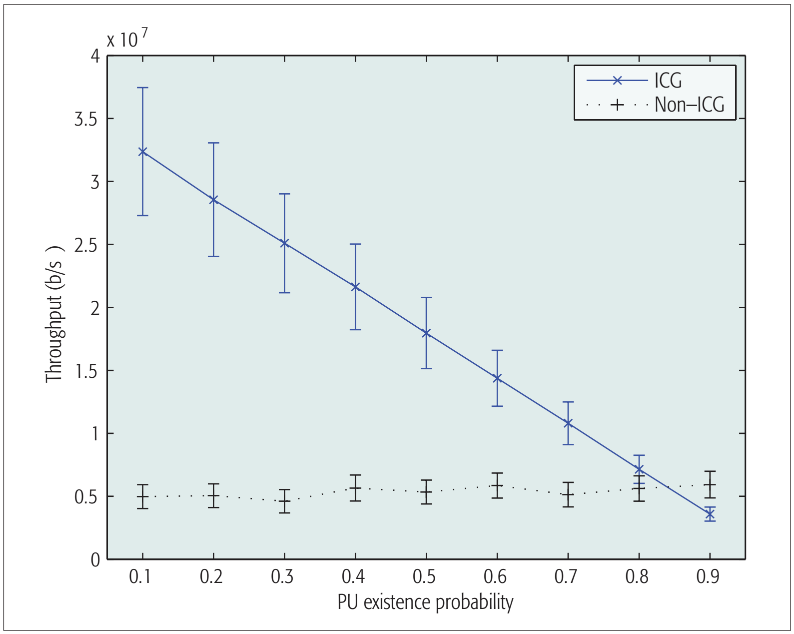


Figure 6. Throughput vs. PU existence probability.

CONCLUSIONS

In this article, we introduce an adaptable and resilient architecture that enables sustainable communication and rapid gathering of crucial event data and its delivery to responder units at the site as well as command and control centers that are off-site. We lay out communication requirements and challenges that should be addressed by the next-generation PPDR network architecture and explain how the proposed solution fulfills these requirements.

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