COGNITIVE RADIO FOR DISASTER RESPONSE NETWORKS: SURVEY, POTENTIAL, AND CHALLENGES

SAIM GHAFOOR, PAUL D. SUTTON, CORMAC J. SREENAN, AND KENNETH N. BROWN

ABSTRACT

In the wake of a natural or man-made disaster, restoration of telecommunications is essential. First responders must coordinate their responses, immediate casualties require assistance, and all affected citizens may need to access information and contact friends and relatives. Existing access and core infrastructure may be damaged or destroyed, so to support the required services, new infrastructure must be rapidly deployed and integrated with undamaged resources still in place. This new equipment should be flexible enough to interoperate with legacy systems and heterogeneous technologies. The ability to self-organize is essential in order to minimize any delays associated with manual configuration. Finally, it must be robust and reliable enough to support mission-critical applications.

Wireless systems can be more easily reconfigured than wired solutions to adapt to the various changes in the operating environment that can occur in a disaster scenario. A cognitive radio is one that can observe its operating environment, make decisions and reconfigure in response to these observations, and learn from experience. This article examines the use of cognitive radio technologies for disaster response networks and shows that they are ideally suited to fulfill the unique requirements of these networks. Key enabling technologies for realizing real-world cognitive radio networks for disaster response are discussed and core challenges are examined.

INTRODUCTION

Disasters are unplanned events that cause significant damage or loss of life. They may also knock out the existing communication networks. The damage to the networks, plus the increased traffic demand, hampers the recovery effort. First responders cannot receive or relay the information they need, victims cannot report their location or request help, and the overall response cannot be coordinated effectively. Quick repair of the communication networks in the critical first period after the disaster could provide a significant boost to the response.

There is a need to rapidly deploy a new flexible infrastructure that can provide immediate services, utilize any existing network resources that are still in place, and interoperate with heterogeneous technologies. The offered system must be reliable and robust enough to support the mission-critical requirements and should be able to self-organize to minimize the delay. Many emerging services based on (2G/3G/4G) mobile systems need to be supported, including different technologies and spectrum bands, each of which may be required in specific locations. In addition, there is a need to discover the extent of the damage: to assess what radio spectrum is available, and what physical access is possible. Obtaining resources to service all of these needs separately, and coordinating their deployment, is a serious challenge.

A Cognitive Radio (CR) [1] can observe its operating environment, make decisions and reconfigure in response to these observations, and learn from experience. A Cognitive Radio Network (CRN) is formed from multiple CRs, and can adapt network-wide behavior in response to the environment. CRNs offer support for heterogeneity, reconfigurability, self-organization, and interoperability with existing networks, and so offer a promising solution for disaster response. For CRNs to be used effectively, we must understand the requirements, enabling technologies, potential issues, and challenges associated with disaster response.

Consequently, in this article our focus is on the potential of CR in disaster response for partially/fully destroyed networks. First we will give an overview of services and requirements for a Disaster Response Network (DRN). Second, the suitability and potential of using CR technology for DRN will be discussed. Finally, we will focus on the remaining research challenges.

DISASTER RESPONSE NETWORKS

A DRN is a communication network that is rapidly deployed in the aftermath of a disaster, to provide necessary services after existing communications infrastructure has been damaged. A number of different standards, technologies, and services are currently used to provide DRNs, and we examine these below.

Saim Ghafoor, Cormac J. Sreenan, and Kenneth N. Brown are with University College Cork, Ireland.

Paul D. Sutton is with University of Dublin, Trinity College, Ireland.

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Disaster Response Network Requirements

DRN requirements have been examined and outlined by a number of national and international bodies, including the US Department of Homeland Security (DHS), the European Telecommunication Standard Institute (ETSI), and the GSM Association (GSMA).

The DHS Program, SAFECOM, has highlighted necessary communication services and their operational/functional requirements for the emergency domain [3]. SAFECOM describes technical requirements for voice/video performance, Quality of Service (QoS), coverage, energy consumption, robustness, and recovery.

ETSI has developed a broad range of work programs for Emergency Telecommunications (EMTEL) to ensure the interoperability and interfacing of services and systems in emergency situations. Among these is TR-102-180, which examines requirements for communication from individuals to authorities/organizations in all types of emergencies. Work program TS-102-181 outlines requirements for communication between authorized representatives who can be involved in the responses and actions when handling an emergency. TS-102-182 examines requirements for communications from authorities/organizations to citizens during emergencies. TR-102-485 examines the spectrum requirements of broadband disaster relief communications equipment. TR-102-745 provides an overview of the user requirements for the application of reconfigurable radio systems in the Public Safety and Disaster Response (PPDR) domain. The Mobile Broadband for Emergency and Safety Applications (MESA) project was an international partnership between ETSI and the Telecommunications Industry Association (TIA) which produced technical specifications for mobile broadband technology for PPDR.

The GSMA Disaster Response Program provides a number of resources for mobile operators, including an overview of technical challenges and requirements associated with preparing for and responding to disasters. The Third Generation Partnership Project (3GPP) also aims to deliver LTE enhancements for public safety in Release 12, considering requirements for spectrum, regulation, application design, coexistence, and migration strategies (VoIP and TETRA). Its two main areas for public safety applications are proximity-based services (SP-120883) and a group communication system enabler for LTE (SP-120876). The inclusion of self-organization capabilities (after Release 8) is relevant to the CR research discussed here. The key factors and considerations for a DRN are outlined in Table 1.

Existing Solutions

A wide range of DRN solutions are currently in use by national and international disaster response organizations. These include network operators, telecommunications equipment vendors, government agencies, and non-government organizations (NGOs). Several United Nations (UN) agencies address the need for communications following disasters, including the Office for the Coordination of Humanitarian Affairs (OCHA), the UN office for Disaster Risk Reduction (UNISDR), the World Meteorological Organization (WMO), the International Telecommunication Union (ITU), and the World Food Program (WFP), which leads the Emergency Telecommunication Cluster (ETC). In this section we examine the existing solutions and assess their key strengths and weaknesses.

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ETC — The ETC provides vital IT and telecommunication services in the event of a disaster. They aim to provide services (voice, data, and Internet connectivity) within 48 hours of the disaster occurrence. The emergency team uses *fly-away-kits* containing equipment necessary to establish communications. Other services include staff, asset, and vehicle tracking based on UHF/VHF, GSM, satellite, and alerting services. For communication services, they provide radio equipment that must be pre-programmed before departure to utilize correct frequency channels for basic coverage around the operational center. This service depends on prior agreement with a host government and communications regulator for spectrum usage. In data/voice connectivity services, they provide Internet connectivity from a single point, and shared Internet connectivity in cafes/offices for wider coverage. Services are restricted according to the available bandwidth. Dedicated Internet backhaul can be provided via Very Small Aperture Terminal (VSAT) satellite links from the affected area. They assist in providing a dedicated GSM/WCDMA/LTE mobile network to be used by the responders in the disaster area. In information management services they provide information and standards for ICT equipment, lists of GSM providers, and availability/reliability of local 2G/3G/LTE data services. ETC provided its initial response for the Typhoon in the Philippines in November 2013 within 24 hours. The emergency communications services provided included Internet connectivity, VoIP, ICT help desk, and radio communication around the main operational area. They used Emerging Markets Communication's VSAT services to provide Internet access to WFP staff, with limited use of Broadband Global Area Network (BGAN). A 12 km Internet link between two operational centers was established by using microwave transmitters. Limits in capacity and disturbances in service delivery were observed due to the frequent movement of staff and relief personnel.

AT&T — AT&T's National Disaster Recovery (NDR) program aims at rapid recovery of AT&T's voice and data network in a disaster situation [4]. Its goals are to route telecommunication traffic and to recover communication services. In addition, the NDR team uses mobile satellite communications for humanitarian relief. Their ECVs, COLTs, COWs, and technology trailers can be deployed to provide calling services to people in affected areas. ECVs can use satellite links to provide broadband LAN, WiFi, and voice (VoIP) connectivity for the recovery site within minutes of arrival with dedicated generators. A 5.8 GHz microwave radio link can also be used to establish communication links from disaster-affected areas to nearby operational sites. A satellite COLT or COW can be utilized

Requirements	Description
QoS	QoS includes parameters such as availability, throughput, latency, jitter and error rate. DRNs frequently carry mission-critical communications services for emergency first responders and so availability and performance consistency is essential. Depending on the capabilities of the deployed network, these services may include live audio and video streams with strict limits on acceptable performance metrics. For example, VoIP calls may require a guaranteed low bit rate with maximum packet delay of 100 ms, jitter of less than 30 ms and packet loss of less than 1% [2]. When a DRN is deployed, service level guarantees must be put in place based on the available resources and achievable QoS.
Robustness and reliability	In a disaster scenario, the radio environment may be changing unpredictably, as the communications infrastructure fails or is repaired, as interferers or high priority critical services occupy the medium, and as physical changes block signals. Any DRN should be robust to such changes, and should aim to provide continual coverage. In addition, many of the services being supported may impose extra reliability requirements, including for example, strict latency guarantees on video for remote medical guidance.
Coverage and mobility	Disasters such as earthquakes, tsunamis and floods frequently affect wide geographical areas. Hurricane Katrina affected an area of 230,000 km^2 in the US in 2005. In these situations, disaster response and management personnel require wide-area connectivity to coordinate relief efforts. Handover between adjacent cells and differing wireless technologies may be needed to ensure seamless coverage of the affected area.
Rapid deployment	Any delay in the response to a disaster may result in further loss of life, injury and damage. DRNs need to be deployed and operational as soon as possible and certainly within first 24 hours following the event to support emergency first responders, permit the affected area to be inspected and assessed and to facilitate the coordination of multiple agencies and authorities.
Interoperability	A DRN may need to link together incompatible communications networks, for example between different groups of emergency responders. Standalone systems can guarantee service availability without relying on the presence of any existing infrastructure in the affected area. However, the capabilities of the DRN and the types of services which it can support may be greatly enhanced by linking into any operational infrastructure which may be available on the ground.
Spectrum agility	A disaster can occur in any location. In order to be deployable across a wide range of locations and environments, a DRN needs to be capable of operating in a wide range of different frequency bands. With sufficient spectrum agility, a DRN can be deployed without prior knowledge and agreement about what spectrum is in use and by whom. Spectrum agility means a DRN can be adapted to local variations in spectrum use and regulation, making it easier to avoid the creation of harmful interference.
Self-organization	A self-organizing DRN can reduce the need for time-consuming initial configuration. As the operating environment of a disaster area can change unpredictably, the ability of a DRN to self-organize also reduces the need for manual reconfiguration in the event of changes in spectrum availability, network topology, user demand etc.
Cost effectiveness	More cost effective DRN systems can be made more readily available and deployed more widely. In considering cost, we must look at the cost of establishing and maintaining the DRN system in readiness for use as well as the actual cost of deploying and running that system. In order to provide services rapidly after a disaster, expensive standalone resources can be put in place. However, in the weeks following the event, these expensive solutions must be transitioned to less expensive, more sustainable configurations.

Table 1. DRN requirements.

to provide cellular communication in areas that have lost coverage due to a disaster. Their technology trailer contains customized telecommunication infrastructure with inter-/intra-city services. In August 2011 NDR used satellite COLTS to provide cellular services to communities in Vermont and New-York following damaging floods.

Table 2 lists the main DRN solutions in use today and assesses each according to the requirements outlined in the second section. Almost all the service providers claim to reach the site within 48 hours of the occurrence of a disaster, but deployment delays can arise due to the need for prior device configuration, the lack of network damage information, the need for prior government and mobile operators agreement for spectrum utilization and customs clearance. The need here is to deploy flexible, ready-to-use, and light weight systems/devices for providing last mile connectivity. For example, Vodafone portable BTS can be deployed easily but cannot fulfill the requirements fully as mentioned in Table 1. Almost all listed solutions involve the use of satellite backhaul systems to provide backend connectivity. While this is an effective approach, it is also expensive and there is a need for flexible systems that can switch to lower-cost backhaul connections if and when they become available. Another major problem is the need for coordination between different service providers and emergency responders. Few service providers offer interoperability, self-organization, or dynamic spectrum utilization. These properties are required for future systems in order to deliver the levels of coordination needed [5].

Organi-zation/ vendor	Solution	Description	Target Users	Services Provided	QoS	Robustness & Reliability	Mobility	Rapid Deployment	Interoperability	Spectrum Agility	Self-organization	Coverage	Cost Effectiveness
Alcatel-Lucent	Broadcast Message Center (BMC)	Gateway for message delivery to GSM/UMTS/CDMA/LTE networks	Mobile subscribers	Alerts and commercial messages by Network Operators	✓	✓	✓	X	✓	X	X	✓	X
AT&T	Emergency Communication Vehicles (ECVs)	Broadband LAN, WiFi, VoIP connectivity, cellular coverage with backhaul as Microwave radio-link of 5.8 GHz	AT&T team, relief personnel	Voice and data services, communication link with AT&T network	✓	✓	✓	✓	X	X	X	✓	X
	Cell on Light Trucks (COLTs) and Cell on Wheels (COWs)	Portable cell site with satellite backhaul	Relief personnel	Cellular communication	✓	✓	✓	✓	X	X	X	✓	X
Cisco TacOps	Cisco Network Emergency Response Vehicle (NERV)	Satellite WAN link, Wide area application services WAAS, Cisco 1240 Wireless AP, Cisco 1500 Wireless Mesh AP, Cisco 7900, 9900 video phones and 7925 IP phones, Call Manager, Tele Presence for video conferencing, IPICS land mobile radio and video surveillance	Community, Relief personnel, NGOs	Voice , video, data and radio communication, Internet connectivity, video conference and surveillance with satellite backhaul, wide area coverage	✓	✓	✓	✓	✓	X	X	✓	X
Delorme	inReach	A satellite based radio	Community, Relief personnel, NGOs	Positioning and messages	✓	✓	✓	X	X	X	X	✓	✓
Disaster Lab Tech	ICT and Communication Services	Internet services and communication network with satellite link (VSAT)	Limited: Community, Relief personnel, NGOs	Limited: Internet access, WiFi networks, VoIP/VPN services, Humanitarian relief	✓	X	✓	✓	X	X	X	X	X
Ericsson Response	Portable Mobile Communication Network Container	GSM/WCDMA based mobile network	Limited: Relief Personnel, Government organizations	Telecommunication and ICT support	✓	✓	✓	✓	X	X	X	✓	X
	WLAN in Disaster and Emergency Response (WIDER)	WLAN hotspot with VSAT as satellite backahul	Limited: Relief personnel	Intranet for information transfer, International voice and Internet	✓	✓	✓	✓	X	X	X	X	X
ETSI/ TCCA	Terrestrial Trunked Radio (TETRA)	Private Mobile Radio (PMR) System	Public safety organizations, Emergency responders	Voice, Data Communication, Special services (Group calls, Messaging, Broadcast)	✓	✓	✓	✓	✓	X	X	✓	X
GVF	Satellite system	Satellite communication	Community, Relief personnel, NGOs	Voice, data and backhaul connectivity	✓	✓	✓	✓	X	X	X	✓	X
Huawei	eLTE	LTE+ broadband trunking solution	Public safety and Relief personnel	Voice, video and broadband communication, Group calls	✓	✓	✓	✓	✓	X	X	✓	X
Inmarsat	BGAN, Isat Phone Pro	Satellite communication	Community, Relief personnel, NGOs	Voice, data and backhaul connectivity	✓	✓	✓	✓	X	X		✓	X
NetHope	Net-Relief-Kit	Solar powered wireless router, ICT and Telecom equipments,	Community, Relief personnel	Humanitarian relief operations with limited ICT services	✓	X	✓	✓	X	X	X	X	X
Telecom Sans Frontier	ICT and Telecommunication support	Mobile network and WLAN with satellite solutions (VSAT, BGAN)	Local community, NGOs, Relief personnel	ICT support, Internet connectivity, voice, data and satellite communication (VSAT, BGAN)	✓	X	✓	✓	X	X	X	✓	X
Vodafone Instant Program	Portable GSM BTS	GSM based network with VSAT as Satellite backhaul	Relief worker and victims	Voice and SMS	✓	X	✓	✓	X	X	X	✓	X

Table 2. DRN capabilities in existing solutions provided by different organizations.

Based on information obtained from the sense/observe process, the CR must then plan a course of action. This may include deciding upon a frequency band to use for establishing network links and choosing an appropriate waveform from a range of available options.

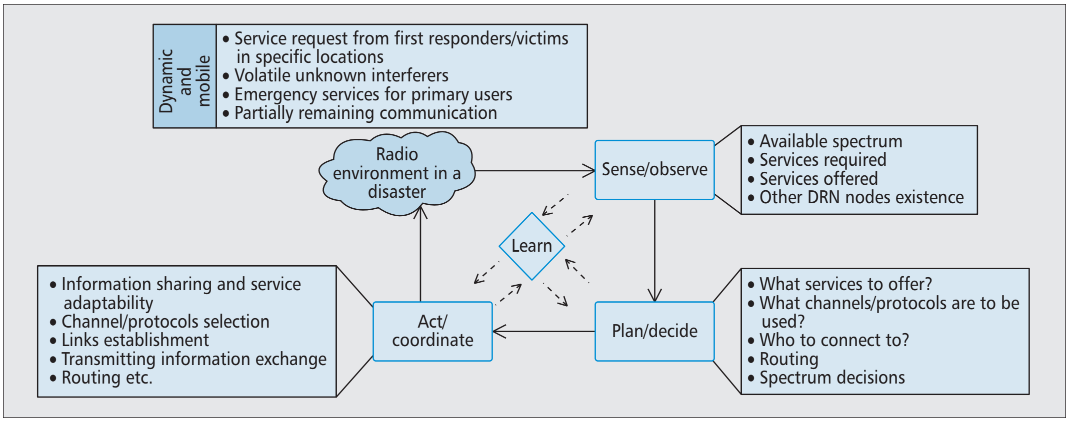

Figure 1. Key cognitive radio mechanisms for disaster response network.

Cognitive Radio for Disaster Response Networks

In 1999 Mitola coined the term cognitive radio and inspired a wave of research into flexible, reconfigurable wireless systems capable of observing their operating environment, choosing appropriate strategies to achieve specific goals, executing those strategies, and learning from past experiences. These capabilities are especially valued in the context of a DRN, where existing communication systems may have been destroyed and new systems must be rapidly deployed in an operating environment about which little may be known and which may change unpredictably. In this section we discuss the current state of CR technology and open issues.

A CR can change its transmitter/receiver parameters based on interaction with the environment and can make decisions based on the available information and predefined objectives [1, 6]. Figure 1 outlines the key mechanisms required by a CR, and we indicate their relevance to DRN. All functions operate simultaneously in parallel, each feeding into the other to adapt to changes in the operating environment. Each function is further described below.

***Sense/Observe* —** Active neighboring wireless systems, available spectrum, and service requests can be detected and possibly identified by observing the operating environment. Such information can be obtained through local sensing, either independently by individual devices or cooperatively as a network of devices. It can also be obtained via databases, either accessed remotely using a network connection or preloaded and accessed locally on the device. In the context of a disaster scenario, a spectrum occupancy database may not be available or may not reflect the situation on the ground, and so local sensing is expected to play the key role. Observations may be retained to build up a map of the operating environment, to detect patterns and to feedback into the sense/observe process by limiting the search space for future observations.

***Plan/Decide* —** Based on information obtained from the sense/observe process, the CR must then plan a course of action. This may include deciding upon a frequency band to use for establishing network links and choosing an appropriate waveform from a range of available options. For example, a waveform with very low out-of-band emissions may be chosen when operating adjacent to a sensitive wireless system. Alternatively, a waveform with higher out-of-band emissions but lower overhead may be chosen when operating in the absence of neighboring systems. The decision-making process may be limited to individual radios, or it may be a distributed process based on shared observations among them. In the context of a disaster, the CR must decide which services are to be prioritized, routing selection for linking heterogeneous systems to existing infrastructure, and protection for critical services, which can be considered as the primary user of the spectrum.

***Act/Coordinate* —** Once decisions have been made and a plan of action formulated, the CR system must execute that plan by sharing and exchanging information (transmission) and service adaptability. Where the system is commencing operation for the first time, this may involve establishing communication links between peer nodes to form the network and start providing services. In the event that the system is responding to a change in the operating environment, it may involve sharing information between peer nodes and adapting together to improve the performance of the DRN. Again, the way in which action is taken in the network may be informed by past experience and learned knowledge about the operating environment.

Cognitive Radio Technology Today

***Regulation* —** In recent years there have been significant developments by regulators to facilitate the deployment of CR technologies. Both Ofcom in the UK and the Federal Communications Commission (FCC) in the US have moved to permit CR systems to operate in TV White Space (TVWS) spectrum following the transition from analog to digital terrestrial television broadcasting. TVWS is the name given to the vacant channels that can be found at different locations due to the frequency reuse patterns adopted by the television broadcast networks. In both the UK and the US, identification of vacant channels is permitted using spectrum sensing or database lookup. Initial power limits and channel detection requirements are quite stringent. However, as stated by Ofcom in their recent consultations, these parameters may be relaxed over time according to the levels of interference experienced. In addition to the UK and the US, regulators in Canada, Singapore, and Ireland are also planning to permit the future use of TVWS spectrum by CR systems.

Standardization — As spectrum regulation has evolved to permit the deployment of CR systems, a number of wireless standards for such systems have emerged. Among these are: IEEE 802.22, a Wireless Regional Area Network (WRAN) standard for rural broadband using TVWS spectrum; IEEE 802.16h, an extension of the original WiMAX standard to support coexistence among license-exempt systems and *Primary Users* (PU); and IEEE 802.11af, an extension of the popular WLAN family of standards to enable deployment using TVWS spectrum. In addition to these efforts, a royalty-free open standard called *Weightless* [7] has been developed for machine-to-machine communications using TVWS in the UK. Weightless was developed primarily by a company called Neul and is currently being further developed by a special interest group with more than 1000 members worldwide.

Enabling Technologies — Along with policy changes enabling the deployment of CR systems, technological developments have brought such systems closer to reality. Software Defined Radio (SDR) is the key enabler for CR systems and, in this space, both RF front-end hardware and available software has developed considerably. Highly integrated programmable, wideband RFIC solutions such as the AD9361 from Analog Devices and the LMS6002D from Lime Microsystems have driven the development of highly capable SDR RF front-ends from companies such as Ettus Research (a National Instruments company), Nuand, and Fairwaves. On the software side, a number of standards-based solutions for general-purpose hardware have emerged. These include OpenBTS, OsmoTRX, OsmoBTS, OpenBSC, and OpenGGSN for GSM and GPRS-based networks. For LTE-based networks, solutions include the LTE100 eNodeB solution from Amarisoft and the OpenAirInterface project from Eurecom. Building upon these technologies are SDR-based companies offering full cellular network deployments such as Vanu, Fairwaves, and Range Networks. In the public safety and military domains, the benefits of SDR-based systems have been leveraged by products such as the Liberty radio from Thales and the XG series from Harris, although both radios are reconfigurable but are not compatible with each other.

Research Projects — The European Framework Program 7 (FP7) and U.S. National Science Foundation (NSF) have funded projects on CR and SDR for the disaster response domain. Some of the projects and awards are mentioned in Table 3. Overall, research on SDR testbeds up to now has focused primarily on Dynamic Spectrum Access (DSA) functionality [8]. Mature, large scale testbeds have not yet been realized in order to fully explore the true meaning of CR as described in [1, 8]. Aspects of the Horizon 2020 Work Programme for 2014-2015 aim to enhance resilience against natural and man-made disasters, including communications interoperability. H2020-DRS-18-2014 focuses on interoperable next generation broadband radio communication systems for PPDR. The scope of this call is to identify and analyze the common communication requirements for PPDR and the gaps in cooperation between organizations in Europe and outside Europe. H2020-DRS-19-2014 focuses on next generation emergency services for voice/video/data/text communications using 112 products over the Internet. The scope of this call is to gather European emergency services organizations, R&D laboratories, and telecommunication-network/VoIP/software/technology providers to build expertise in a collaborative manner.

Cognitive Radio Potential and Challenges for Disaster Response Network

CR technology is already evolving for use in military and commercial domains. However, many of the capabilities enabled by the technology have significant potential for use in future DRNs. DSA is often considered the key application of CR, but there are many other potential ways in which CR can be applied for DRN systems. Currently large scale disaster deployments with dynamic spectrum utilization still needs research [8, 9]. In Fig. 2, a DRN scenario is shown where NGOs and first responders establish their initial setup in an operation center. Static/mobile Cognitive Radio Base Stations (CRBSs) can be used to provide the extended voice/data and radio connectivity, with backend connectivity to the operation center through these CRBS in a multihop manner or with UAVs. The operation center can be connected to the global Internet via satellite/backhaul links or to other nearby base stations/disaster-sites through multihop CRN.

In a disaster scenario, we consider the DRN a Secondary User (SU) and the existing/partially destroyed network a PU. In this way it is the responsibility of the newly deployed DRN to avoid the creation of harmful interference for already existing systems. Several researchers have highlighted the role of PUs and SUs in a disaster situation, such as [10]. If the SU detects a PU in the course of operation, it reconfigures its operation in order to avoid causing interference. Below we examine some of the potential benefits of CR in the context of the DRN requirements outlined previously with remaining challenges.

QoS — For a policy-driven CR system, QoS requirements can be used to define those policies. As the operating environment changes, the system may need to adapt to maintain the required QoS parameters. For a disaster scenario, it may be necessary to define multiple service levels that are driven by specific application requirements. In the event that resources are not available to provide a particular service level, the

In the public safety and military domains, the benefits of SDR-based systems have been leveraged by products such as the Liberty radio from Thales and the XG series from Harris, although both radios are reconfigurable but are not compatible with each other.

Project	Funding body	Duration	Objectives
ABSOLUTE	FP-7	2012-2015	The ABSOLUTE project is aiming to deliver the cognitive concepts for dynamic spectrum management by seamless network reconfigurability. Another goal is to provide a rapidly deployable mobile network to provide broadband services.
CORASAT	FP-7	2012-2015	To investigate, develop, and demonstrate cognitive radio techniques in satellite communication systems for spectrum sharing.
CREW	FP-7	2010- 2015	To establish an open federated testbed platform, which facilitates experimentally-driven research on advanced spectrum sensing, cognitive radio and cognitive networking strategies in licensed and unlicensed bands.
EULER	FP-7	2009-2012	To improve the interoperability of civil forces in crisis situations using the benefits provided by SDR.
DITSEF	FP-7	2010- 2013	To provide self-organizing and robust ad-hoc communications where the existing infrastructure is compromised and sensors for overview and threats of the situation.
SALICE	NRF, Italy	2008- 2010	To identify the solutions which can be adopted in an integrated reconfigurable NAV/COM device and studying its feasibility in realistic scenarios. The first goal of the SALICE project is to define the baseline scenarios and system architecture for integrated communications and localization techniques, SDR NAV/COM devices, satellite and HAPS integration in the rescue services, heterogeneous solutions in the area of intervention.
EMPHATIC	FP-7	2012-2015	To develop and demonstrate the capability of enhanced multi carrier techniques to make better use of existing radio frequency bands in providing broadband data services in coexistence with narrowband legacy services. Cell based and Ad-hoc based solutions for PPDR will be developed in it.
CNS/EARS	NSF	until 2014	Enhancing Access to the Radio Spectrum aims at cognitive and reconfigurable wireless systems. Including spectral efficiency, reconfigurable wireless systems, security of wireless signals and systems, coexistence with legacy systems, special-purpose wireless systems with tests and measurements, economic model for spectrum sharing, spectrum management techniques, network radio architecture and energy efficient and robust spectrum sensing and allocation techniques. Several projects in this scheme are aiming at large scale heterogeneous scenarios.
CNS/RSCRN	NSF	2011-2014	Robust and Secure Cognitive Radio Network project is mainly focusing on coexistence issues of secondary users with primary networks, operating in same frequency bands. It is also focusing on radio resource management schemes and designing low overhead distributed algorithms addressing security issues.

Table 3. Projects related to cognitive radio and disaster response.

system could then adapt to ensure that the next level is supported. One example of this could be a CR system that operates initially using the UHF band. If the band becomes congested, the achievable throughput might fall below the threshold required for streaming video services. In response, the system might reconfigure to detect a vacant channel, for example in the 2.4 GHz ISM band, and provide services using that channel instead.

To meet QoS requirements, it is important to maintain the level of reliability and end-to-end delay minimization while switching between available spectrum bands [11]. The need for spectrum sensing in a CRN can introduce latency to the network, therefore short sensing times and quick PU detection are needed to reduce the packet transmission delay [12]. If a spectrum band switch is required, the use of pre-arranged backup channels and rapid rendezvous techniques can minimize the delay involved [13]. Such spectrum management mechanisms may involve cross layer solutions.

Robustness and Reliability — CR is ideally suited to provide the robustness required for a DRN. The ability of the system to continually sense its environment and reconfigure to achieve its QoS and reliability requirements means that it can adapt to the changing environment. Adaptive and efficient transmission techniques with high reliability can be used to avoid link failures. For instance, if a link fails between two mobile nodes due to increasing distance, it can be recovered by changing locations, changing the modulation scheme, and switching to a lower frequency with lower path loss.

Further, wideband transmission techniques (frequency hopping, spread spectrum, OFDMA etc.) can also be used to increase the reliability in environments with high interference. A reliable channel can then be selected based on interference, attenuation, shadowing, and fading. To achieve this, higher-accuracy sensing is required.

Coverage and Mobility — A CR system could offer an advantage in providing coverage and mobility by acting as the glue to repair a damaged cellular network. Highly-flexible SDR systems can adapt to multiple standards and services using a common radio interface and general-purpose processing hardware. Such systems could replace damaged cellular sites, providing multiple services over, for example, GSM, TETRA, APCO P25, HSPA, or LTE. Services could be provided and resources should be allocated according to demand. The same ability to provide multiple different standards and services makes CR an ideal solution for linking together heterogeneous wireless communications systems to ensure coverage of an affected disaster area.

Current DRN communications approaches often target pre-specified areas, resulting in patchy coverage of the disaster scenario. The use of DSA techniques, coupled with multihop network architectures, can provide wide area coverage with high bandwidth efficiency, as illustrated in Fig. 2. However, multihop CRNs involve challenges such as spectrum sharing/mobility, optimal relay-node selection, end-to-end delay, and interference avoidance [14]. The frequent mobility of CR users affects the topology that relies mostly on the neighbor information. Efficient coordination and spectrum/node selection mechanisms are needed to overcome spectrum availability and service priority constraints. Due to the high cost of satellite based solutions, alternative backhaul solutions and proper channel selection strategies are required [10].

Rapid Deployment — The plug-and-play nature of CR systems can increase the speed with which DRN systems can be deployed. The time needed to configure and tune the network can be greatly reduced by setting a policy for the system and allowing it to operate on the basis of that policy.

CRNs using a DSA approach can use spectrum sensing to build an RF map of the area of operations in order to reduce deployment times [15]. To assess damage and service requirements, emergency personnel can carry auto-configuring CR devices to affected areas in the immediate aftermath of a disaster. These CRs can carry out spectrum sensing and use ad-hoc, multihop, and mesh networking techniques [16, 17, 18] to relay information using delay-tolerant applications. Following initial assessment, mobile/static CRBSs can be used to extend connectivity and provide services to inaccessible regions, as shown in Fig. 2.

Interoperability — General-purpose RF and baseband processing solutions, coupled with CR techniques including DSA, can offer key benefits when it comes to interoperability. In a disaster response environment, different communication systems with different standards and service providers are often deployed, reducing the risks associated with reliance on any single system. However, the operation of these systems in isolation can lead to increased resource constraints and siloing of information. Software radio-based CRs can overcome these issues by providing gateways and bridges between incompatible networks, supporting multiple standards and waveforms in a single device, and providing increased service accessibility. Flexible UAV-based interoperable systems offer an additional dimension of connectivity, as illustrated in Fig. 2.

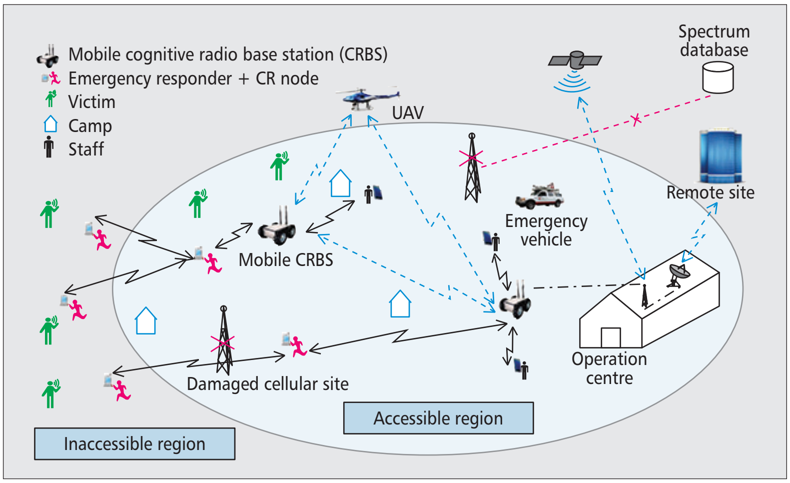

Figure 2. Response scenario for an area after communication is destroyed.

Many challenges still need to be addressed before such software radio-based CRs can be reliably deployed [19, 20]. However, as discussed in previous sections, technological and regulatory hurdles associated with these systems continue to be overcome.

Spectrum Agility — Spectrum agility is another key benefit of CR technology when applied to disaster response networks. The geographical location of a disaster cannot be predetermined, so DRN systems should not be limited to specific regions. Spectrum regulations can vary greatly between different countries, and even within a single standard such as LTE over 40 different spectrum bands may be used in different regions of the world. Spectrum agile CR systems can adapt to the regulations and spectrum environments of any geographical location. When used to temporarily replace damaged infrastructure, they can replicate the spectrum usage of that infrastructure, and when providing independent wireless coverage or relay links, they can avoid the creation of harmful interference using DSA techniques.

Spectrum database-based approaches are emerging as the preferred option for DSA systems in non-DRN scenarios due to the reduced device cost and complexity they can provide. Database approaches also offer regulators greater control over deployed DSA systems. However, use of a spectrum database requires that database to be in place before a DSA system can be deployed, as well as a reliable communications infrastructure to support access to it. In a DRN scenario, such a database may not exist for the region affected, and existing communications infrastructure is often damaged or destroyed. Therefore, spectrum sensing approaches for DSA may be preferred for DRNs. As discussed above, challenges associated with spectrum sensing include minimizing the delay introduced to the network while ensuring sufficient sensing performance to avoid the creation of harmful interference.

Self-organization — The delay-sensitive nature of disaster scenarios demand adapting the spectrum configuration and decision making at runtime to avoid the need for manual configuration of wire-

DRN requirements	CR potential	Issues and challenges
QoS	• Adaptability to maintain QoS levels in dynamic environments • Policy management based on QoS requirements	• Sensing time optimization to minimize packet transmission delay • Efficient QoS level switching according to resource availability and application demands • Maintenance of end-to-end path reliability
Robustness and reliability	• Repeated sensing, parameter selection and reconfiguration • Learning from experiences • Reliable frequency and robust transmission technique selection	• Minimized frequency switching delay in case of failure • Algorithms for shorter decision time with accuracy/reliability • Spectrum aware routing algorithms for high spectrum variation • Collaborative and distributed sensing algorithms • Reliable channel assignment and robust transmission strategies
Coverage and mobility	• Repair and extend the partially damaged cellular network • Support heterogeneous wireless systems and spectrum • Wide area coverage using heterogeneous frequencies • User mobility support with delay tolerance	• Efficient DSA techniques • Multihop communication for high bandwidth and wide area coverage • Efficient spectrum selection/sharing/mobility mechanisms • Efficient coordination among neighbors • Optimal relay node selection • Maintaining dynamic topology and end-to-end paths due to frequent mobility • Coverage extension techniques for last mile connectivity • Alternate solutions for backhaul connectivity • Delay tolerant mechanisms for sensitive data services (voice, video)
Rapid deployment	• Reduced delay associated with device pre configuration and spectrum planning • Plug-and-play networks	• Ready to use, lightweight CR systems • Policy management for operation in critical environments • Optimal spectrum utilization with low interference • Algorithms for dynamic network topologies (ad-hoc/multihop/mesh) • Minimized network/neighbor discovery time • Reliability prior to core network replacement/repair
Interoperability	• Serve as single gateway between different communication systems • Flexible resource sharing among heterogeneous networks and spectrum • Dynamic bandwidth access/waveform selection • Reconfigurability and adaptability of operating parameters • Provision of multiple standards and services using a common radio interface	• Linking heterogeneous systems while ensuring service accessibility • Seamless communication and coordination among different operators and systems • PHY/MAC cross-layer design of efficient DSA functions for heterogeneous networks • Robust gateway platforms with optimized protocols • Network identification for coexistence management
Spectrum agility	• Wide spectrum range support • Efficient DSA functions for topology management • Spectrum utilization based on previous experience • Adaptation to region-specific regulations	• Spectrum detection techniques for interference avoidance • Optimized spectrum sharing techniques • Spectrum mobility techniques to maintain QoS levels • Disruption tolerance mechanisms • Interference minimization and congestion avoidance mechanisms for low packet drop rate • Sensing time optimization • Advanced interference management techniques
Self-organization	• Real time system configuration and decision making • Reduced manual configuration to minimize the number of technicians on the ground • Automatic neighbor/network discovery • Reconfiguration and DSA Management to adapt operating parameters	• Machine learning algorithms to avoid manual configuration/maintenance • Distributed communication techniques with local negotiation • Efficient spectrum hand-off mechanisms • Optimal route selection in ad-hoc/mesh CRNs • Location aware radios, networks and applications for emergency responders
Cost effective-ness	• Lower deployment/maintenance costs • Multi-standard basestations/gateways • Fewer specialists and technicians on ground • Less expensive backhaul connectivity	• Robust and flexible gateway for multiple services and platforms • Mesh networking for low-cost backhaul • Low cost inter-/intra-network communication • Low cost SDR/CR devices • Energy efficient algorithms • Protocol optimization to minimize backhaul traffic

Table 4. Research potential, issues and challenges for cognitive radio in disaster response domain.

less systems and devices. Self-organization can reduce the delays related with deploying and running a network, and can decrease operational cost by eliminating the need for manual configuration and maintenance of the network. Self-organizing CR systems with dynamic spectrum management capabilities can provide neighbor/network discovery and node/route selection, requiring fewer specialist technicians on the ground during deployment and operation.

CR systems can provide high spectrum use efficiency and wide area coverage through spectrum agility over a wide range of frequencies. Self-organization with the network can reduce delays associated with spectrum hand-off, enable coordination among distributed CRs, and support local spectrum allocation/sharing negotiations between devices. Decentralized approaches can eliminate single points of failure and increase network robustness.

Cost Effectiveness — Restoration of different services and technologies at the time of a disaster may require the deployment of separate devices for each service. Instead of deploying multiple base stations for multiple technologies and services, deployment of just a single flexible gateway that can fulfill the demands for standards and services can help reduce the deployment and operational cost. A significant cost associated with DRN systems is due to the use of satellite solutions for access and backhaul. By providing a flexible system that can link into any functional core network resource, these costs can be greatly reduced. Alternate backhaul solutions can be provided using CR based mesh networks to connect, for example, surviving base stations.

As discussed in the previous section, self-organizing capabilities can greatly reduce the cost associated with preconfiguring and maintaining a DRN by reducing the need for skilled technicians on the ground. CR based gateway/bridge systems can reduce the cost of establishing and maintaining inter-/intra-network communications. Table 4 further outlines the potential benefits and challenges of CR technology for the disaster response domain.

Conclusions

This article has described the operational and technical requirements for DRNs and has provided an overview of existing wireless solutions used by emergency response organizations and personnel. CR technology has the potential to be an effective tool for DRNs through the ability to self-organize and adapt operating parameters to the observed environment. Many challenges remain to be overcome in order to realize this potential. These range from robust spectrum sensing techniques to cross-layer spectrum management solutions, and from routing protocols for dynamic network topologies to seamless integration of heterogeneous wireless systems. We have assessed the potential for CR technology in DRN solutions, and we have outlined the key challenges that remain to be addressed in future work. By overcoming these challenges, CR technologies can be leveraged to play a prominent role in future mission-critical situations.

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References

[1] J. Mitola III and G. Q. Maguire, "Cognitive Radio: Making Software Radio More Personal," *IEEE Pers. Commun.*, vol. 6, no. 4, Aug. 1999.

[2] C. Lewis and S. Pickavance, "Implementing Quality of Service," *Selecting MPLS VPN Services*, 1st ed., Pearson Education, 2006, pp. 139–85.

[3] SAFECOM, US communications program of the Department of Homeland Security, "Public Safety Statements of Requirements for Communications and Interoperability Vols. I and II."

[4] K. T. Morrison, "Rapidly Recovering from the Catastrophic Loss of a Major Telecommunications Office," *IEEE Commun. Mag.*, vol. 49, no. 1, 2011, pp. 28–35.

[5] G. Baldani *et al.*, "Survey of Wireless Communication Technologies for Public Safety," *IEEE Commun. Surveys Tutorials*, vol. 16, no. 2, Sept. 2013, pp. 619–41.

[6] I. F. Akyildiz *et al.*, "A Survey on Spectrum Management in Cognitive Radio Networks," *IEEE Commun. Mag.*, vol. 46, no. 4, April 2008, pp. 40–48.

[7] W. Webb, "Weightless: The Technology to Finally Realise the M2M Vision," *Int'l Journal of Interdisciplinary Telecommunications and Networking (IJITN)*, vol. 4, no. 2, April 2012, pp. 30–37.

[8] P. Pawelczak *et al.*, "Cognitive Radio: Ten Years of Experimentation and Development," *IEEE Commun. Mag.*, vol. 49, no. 3, March 2011, pp. 90–100.

[9] P. Steenkiste *et al.*, "Future Directions in Cognitive Radio Network Research," NSF Workshop Report, March 2009.

[10] M. H. Rehmani *et al.*, "A Cognitive Radio based Internet Access Framework for Disaster Response Network Deployment," *Proc. 4th International Workshop on Cognitive Radio and Advanced Spectrum Management (CogART)*, Nov. 2011, pp. 1–5.

[11] E. Onem *et al.*, "QoS-Enabled Spectrum-Aware Routing for Disaster Relief and Tactical Operations over Cognitive Radio Ad-hoc Networks," *Proc. IEEE Military Communications Conference (MILCOM)*, Nov. 2013, pp. 1109–15.

[12] C. L. Wang, H. W. Chen and Y. X. Cheng, "Sensing-Delay Trade-off for Cognitive Radio Networks with QoS Considerations," *Proc. IEEE 78th Vehicular Technology Conference (VTC)*, Sept. 2013, pp. 1–5.

[13] P. D. Sutton, K. E. Nolan, and L. E. Doyle, "Cyclostationary Signatures in Practical Cognitive Radio Applications," *IEEE JSAC*, vol. 26 , no. 1, Jan. 2008, pp. 13–24.

[14] A. Azarfar, J. F. Frogon, and B. Sanso, "Improving the Reliability of Wireless Networks using Cognitive Radios," *IEEE Commun. Surveys Tutorials*, vol. 14, no. 2, May 2012, pp. 338–54.

[15] H. B. Yilmaz *et al.*, "Radio Environment Map as Enabler for Practical Cognitive Radio Networks," *IEEE Commun. Mag.*, vol. 51, no. 12, Dec. 2013, pp. 162–69.

[16] I. F. Akylydiz, W. Lee, and K. R. Chowdhury, "CRAHN: Cognitive Radio Ad-hoc Networks," *Journal of Ad-Hoc Networks*, vol. 7, no. 5, July 2009, pp. 810–36.

[17] S. Sengupta and K. P. Subbalakshmi, "Open Research Issues in Multihop CRNs," *IEEE Commun. Mag.*, vol. 51, no. 4, April 2013, pp. 168–76.

[18] K. R. Chowdhry and I. F. Akyildiz, "Cognitive Wireless Mesh Networks with Dynamic Spectrum Access," *IEEE JSAC*, vol. 26, no. 1, 2008, pp. 168–81.

[19] K. E. Nolan *et al.*, "Demonstration and Analyses of Collaboration, Coexistence, and Interoperability of Cognitive Radio Platforms," *Proc. IEEE 4th Consumer Communications and Networking Conf. (CCNC)*, Jan. 2007, pp. 1149–53.

[20] T. Ulversoy, "Software Defined Radio: Challenges and Opportunities," *IEEE Commun. Surveys Tutorials*, vol. 12, no. 4, 2010, pp. 531–50.

Biographies

SAIM GHAFOOR (saim.ghafoor@insight-centre.org) is a Ph.D. student at University College Cork, Ireland, since December 2012. His work is focused on optimization techniques in Cognitive Radio Networks. He did his master's degree in Computer Science and Engineering from Hanyang University, South Korea. His research interests are wireless sensor

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networks, cognitive radio networks, and delay/disruption tolerant networks.

PAUL D. SUTTON (suttonpd@tcd.ie) is the founder of Software Radio Systems Ltd., based in Cork and Dublin, Ireland. He is a research fellow at CTVR, the Telecommunications Research Centre, based at Trinity College Dublin, and has been actively involved in the research and development of emerging wireless technologies since 2004. In this time his work has addressed key challenges in the areas of dynamic spectrum access and cognitive radio through the use of technologies including cyclostationary signal analysis, adaptive multicarrier waveforms, and software radio. He received his Ph.D. in electronic engineering from TCD in 2008. He served on the board of the Wireless Innovation Forum from 2009 to 2013.

CORMAC J. SREENAN (cjs@cs.ucc.ie) received the Ph.D. degree in computer science from Cambridge University. He is a full professor of computer science at University College Cork (UCC) in Ireland. Prior to joining UCC in 1999 he was on the Research Staff at AT&T Labs-Research, Florham Park, NJ, and at Bell Labs, Murray Hill, NJ. He is currently on the editorial boards of *IEEE Transactions on Mobile Computing*, *ACM Transactions on Sensor Networks*, and *ACM/Springer Multimedia Systems Journal*. He is a member of the IEEE and the IEEE Computer Society and was elected a Fellow of the BCS in 2005.

KENNETH N. BROWN (k.brown@cs.ucc.ie) is a senior lecturer in the Department of Computer Science at University College Cork, and is a member of CTVR, the Telecommunications Research Centre, and Insight, the Data Analytics Research Centre. He has been a member of the executive committee of CTVR since 2006. His research concerns applications of artificial intelligence in areas such as wireless networking and resource allocation, with a particular interest in distributed, dynamic, and uncertain problems.