CANUS Border Radio Coverage - Technology Solutions

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4.0 List of Acronyms

1x EV-DO	1x (single carrier) evolution data optimized
1xRTT	1x (single carrier) radio transmission technology
2G	Second generation (mobile cellular phone networks)
3G	Third generation (mobile cellular phone networks)
A/D	Analog to digital
AMSC	American mobile satellite corporation
API	Application programming interface
ASIC	Application specific integrated circuit
BS	Base station
CAI	Common air interface (P25 context)
CBD	Component Based Development
CDMA	Code division multiple access
CORBA	Common object request broker architecture
CPRI	Common public radio interface
CR	Cognitive radio
CRC	Communications Research Centre
CS	Circuit switch
DoD	Department of Defence (US)
DRDC	Defence Research and Development Canada
DSA	Dynamic Spectrum Allocation
DSP	Digital signal processor
EDGE	Enhanced Data for GSM Evolution
FDMA	Frequency division multiple access
FFB	Free floating balloons
FPGA	Field programmable gate array
GEO	Geostationary earth orbit
GHZ	Giga hertz
GPP	Generation partnership project (1^{rst}, 2^{nd},3^{rd} generations 1-GPP, 2-GPP, 3GPP) (context)
GPP	General purpose processor (context)
GPRS	General Packet Radio Service
GPS	Global positioning system
GSM	Global system for mobile communications
HSPA	High Speed Packet Access
IEEE	Institute of electrical and electronics engineers
IF	Intermediate frequency
IMT	International Mobile Telecommunications
IP	Internet protocol
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union – Radio communications sector
ISI	Inter-system interface
LAN	Local area network
LEO	Low earth orbit
LoS	Line of sight
LTE	Long Term evolution
MAC	Medium access control
MANET	Mobile ad-hoc network
MEO	Medium earth orbit
MHz	Mega hertz
MIMO	Multiple-in, Multiple-out
MWAN	Mobile wide area network
OFDM	Orthogonal frequency division multiplexing
OS	Operating system
POSIX	Portable operating system instruction set

P25	Project 25 Radio Technology
PS	Public safety (context)
PS	Packet switch (context)
PSTN	Public switched telephone network
PTT	Push to talk
QoS	Quality of Service
RF	Radio frequency
PSTN	Public Switched Telephone Network
RFSS	RF Sub-system (P25 context)
RRM	Radio resource management
RTB	Research test bed
RTP	Real time protocol
SA	Situation awareness
SCA	Software Communications Architecture
SDR	Software Defined Radio
TCP	Transmission control protocol
UAV	Unmanned Aerial Vehicle
UDP	User datagram protocol
UMA	Unlicensed mobile access
UMTS	Universal Mobile telecommunications system
VoIP	Voice over internet protocol
WAN	Wide area network
WCDMA	Wideband code division multiple access
WiFi	Wireless Fidelity
WiMax	Worldwide interoperability for microwave access
WinnF	Wireless Innovation Forum
WWW	World wide web

5.0 Introduction

The main factor that limits the coverage of terrestrial public safety networks is the lack of wireless communications infrastructure to support mobile workforces. This can be seen clearly in coverage maps (see other Reports from the CANUS Border Radio Coverage project), where the gaps identified essentially occur in areas with difficult terrains, or with a low population density (i.e. with a reduced or non-existent road network).

These areas are underserved in terms of public safety communications mainly because of the low occurrence of emergency events and the low incentive to install a costly communications infrastructure. Hilly terrains, deep valleys, large water bodies, foliage density, and other related natural impediments have an intrinsic lower risk of public safety event occurrences because the smaller population density. Providing radio coverage of these areas increases the cost of the existing infrastructure. The nature of mountainous geographical areas also adds to the coverage problem, by creating zones where radio propagation is more difficult. It is often the shadowing effects of irregular terrain, buildings, and other objects that limit the effective communication range, as opposed to the transmit power levels or system gains.

This report provides a study of various communication technologies that Public Safety organizations could use to bridge the various coverage gaps identified in the previous sections. In the following sections, the attention will be focused on solutions that may supplement the infrastructure and/or that leverage the recent advances in protocol design.

- Section 6.0 discusses a variety of solutions that could be used to increase the coverage with contemporary technologies.
- Section 7.0 reviews advanced or emerging wireless technologies, providing different new alternatives to extend the radio coverage.
- Section 8.0 covers how these emerging technologies could be used to provide the required radio coverage extension.
- Finally, Section 9.0 establishes a roadmap for future actions by the Public safety to minimize the coverage gaps.

6.0 Coverage Extension Solutions using Current Technologies

Public Safety organizations in Canada require wireless technologies to provide high availability and ubiquitous communications in particular along the Canada-US border. This becomes increasingly difficult as some of the target coverage areas are far from any existing infrastructure. These applications require reliable long-range communications, to support both strategic and tactical communications, even in the most challenging environments where difficult terrain is the norm. This is not always the case as presented in the previous reports of this study: the coverage of wireless analog voice communication has many gaps along the Canada-US border.

In this Section, a number of options, based on currently available technologies, are reviewed to identify their potential for coverage gap reduction.

6.1 Public Safety Fixed Infrastructure Extension

This section explores solutions that are based on infrastructures owned and controlled by the Public Safety organizations.

6.1.1 New Tower sites

Adding new fixed tower sites, dedicated to Public Safety, either as repeaters or new Base Stations (BS) is the obvious choice. However such a solution is likely to be very costly, making it difficult to consider as a viable option. The easily accessible sites (rooftop of police or fire stations) are already equipped with antennas. To reduce the coverage gaps, the new tower sites would need to be built in isolated and access-limited areas.

Note that this option could become attractive if a partnership with external entities could be made to share the deployment cost. Such entities could be, for example, commercial cellular operators or public service and private organizations (hydro, forest companies, broadcasters, wireless internet providers…). These options are discussed briefly in subsequent sections.

6.1.2 Modify Existing Sites

Existing sites are often equipped with omnidirectional antennas providing global coverage, but insensitive to the terrain profile and propagation characteristics. A significant number of gaps could most likely be reduced by adding, to some of the existing BS sites, directional antennas to service specific sectors.

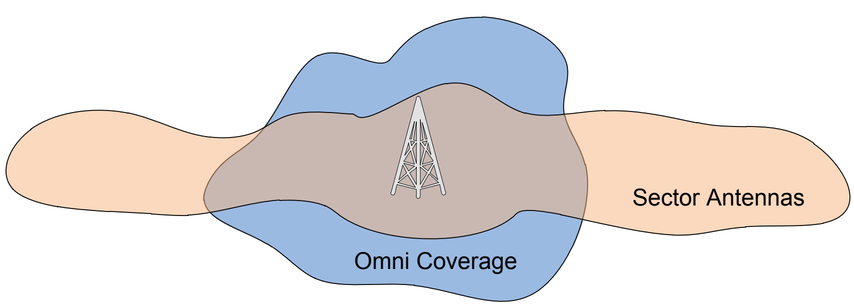

Figure 1 Modified antenna pattern

In addition to a modification or addition of antennas, a change of frequency could be used to provide better wireless coverage. Coverage is based on a link budget, which in turn is affected by transmit power, propagation loss and receiver sensitivity. The propagation loss is very much dependent on the frequency. A frequency "sweet spot" exists near 700 MHz, since propagation loss is still quite acceptable but the frequency is high enough such that electromagnetic noise (man-made or natural) is less than at lower frequencies. This option would be costly as a renewal of the mobile communications equipment would be needed to support those new frequencies. A software defined radio approach, as will be discussed in a following Chapter might be an option for future acquisition.

Such solutions are however very much site specific. The achievable improvement will depend greatly on the surrounding terrain configuration. A detailed analysis of each site would need to be conducted before this option could be adopted.

6.2 Rapidly Deployable Infrastructure

In addition to the addition or modification of permanent infrastructure elements, the coverage can be temporarily extended with the help of transportable equipment. In this section, a number of these rapidly deployable options are reviewed.

6.2.1 Temporary Mast

There are several different types of temporary masts available today. Depending on the height, weight, available footprint and wind load requirements, these can vary from a light-duty man-portable fiberglass kit, to trailer mounted pneumatic and/or electrical winch masts for heavy-duty deployments.

Figure 2 Temporary mast deployment

6.2.2 Aerostat - Tethered

Aerostats can be used as an alternative to towers. Essentially, an aerostat is a lighter-than-air object that can be raised above ground level, while remaining in a relatively fixed position. It can then be used to greatly improve the line-of-sight coverage of a base station radio to a number of end users located at ground level.

Typical costs for the procurement of a small aerostat ranges in the area of $1M/piece. To this, one must add some helium to inflate. Aerostat manufacturers include:

- Lockheed Martin
- TCOM
- Aeros Corporation

Figure 3 Aerostat as repeater

6.2.3 Free Floating Balloons – Tethered or non-Tethered

Similar to an aerostat, a free floating balloon (FFB) is a lighter-than-air object but much smaller in scale. As a result, their payload (what they can carry/lift) is lighter. An FFB can be tethered or non-tethered, depending on the application.

The procurement cost, which includes the payload, the balloon, the launch and control station is typically $180k. Additional payload is approximately $10k each, and extra balloon, $300 each. The balloons will remain in the air for approximately 8 hours and can be reused (if recovered in the case of non tethered).

The main supplier of FBB is Space Data.

Figure 4 Free floating balloon repeater

6.2.4 Unmanned Aerial Vehicles

An unmanned aerial vehicle (UAV) is an aircraft that is flown by qualified personnel, usually pilots, from a ground control station since there is no human crew onboard. A UAV can vary in size, to accommodate different payloads and flight time. In order to create lift, the UAV must keep moving, but this is done in an automatic controlled manner called loitering (or orbiting), which provides a stable radio coverage environment.

Like anything else, the price range for UAVs can vary quite drastically. Starting with the small form factor at $50K [1],[2], to $10M for mid-size and popular ones [3], and up to $35M for large size and the most sophisticated ones [4]. The small tactical UAVs would be best suited to fill the gaps during public safety events.

The main manufacturers of UAVs include:

- AeroVironment Inc.
- General Atomics Aeronautical Systems
- Northrop Grumman
- Lockheed Martin
- Boeing.

The Ottawa branch of the Defence Research and Development Canada laboratory (DRDC-Ottawa) has a research test bed (RTB) being used by the Canadian Forces Experimentation Centre, among others, to simulate UAVs in complex scenarios in the context of training, mission rehearsal, as well as vehicle and sensor evaluation [5]. There is a possibility of collaborating to experiment a number of PS scenarios.

Figure 5 Unmanned aerial vehicle (UAV) repeater

6.3 Commercial Networks

6.3.1 Commercial Cellular Networks

Commercial cellular networks are well distributed along the Canada-US border, with the 2G GSM and/or CDMA2000 1xRTT technologies being available in the most densely populated areas. 3G technologies have been gradually deployed in most urban areas over the last few years. Figure 6 to Figure 8 provide a view of Bell Mobility 2G (1xRTT) coverage along the border [6]. The coverage for the higher speed 1xEV-DO system is shown in Figure 9. As can be seen, there are large portions along the border that are not covered by commercial networks, essentially corresponding to unpopulated and isolated areas.

Existing commercial cellular networks can therefore be used to extend the coverage in populated areas, but are of limited use in most of the areas where private public safety networks experience major shortcomings.

One must however recognize the specificity of the commercial cellular network versus the requirements of the Public Safety communications. The most important requirements are: availability, survivability, security, and control [7].

Availability: Public safety networks need a very high availability to ensure that mission critical communications can be established. Network availability requirements of 99.999 percent are not uncommon, meaning a down turn of less than 5 minutes per year. Public carrier network also have high degree of availability, but the service is shared with the consumer market. In times of crisis, the network performance can be degraded dramatically, as a result of network congestion. Techniques to offer guaranteed access (dial tone availability and non-dropping calls) do exist, but experience shows that they are not enforced by the cellular operators.

Survivability: Survivability is defined as the ability to continue to deliver the essential services in the presence of attacks, failures or accident. Private networks can be engineered to afford a high degree of survivability by including different levels of redundancy (tower sites, frequencies, protocols, power backup…). Of course, survivability comes at a cost. Commercial carrier networks, while quite reliable to maintain their consumer base, are most often designed to sustain short duration abnormal situations such as mild storms, small earth quakes, flood. In case of more severe environmental events or terrorist attacks, those systems would likely fail.

Security: Protection of sensitive data and access control to the network are two essential features of public safety agencies. Both private and public network offer high level of security. To provide additional security, the Public Network could operate under a virtual private network (VPN) configuration. This would also ensure a more seamless interoperability with military assistance.

Control: One of the benefit of owning its infrastructure is the total freedom for its design (frequency, power, protocol, site locations). Of course, cost must be considered in the implementation equation. Public cellular networks are designed to serve the consumer market and meet business objectives, which may not always be compatible with the public safety requirements. Frequency bands and system availability are the major differences between the two systems.

Figure 6 Bell Mobility 1xRTT Quebec/Ontario coverage [6]

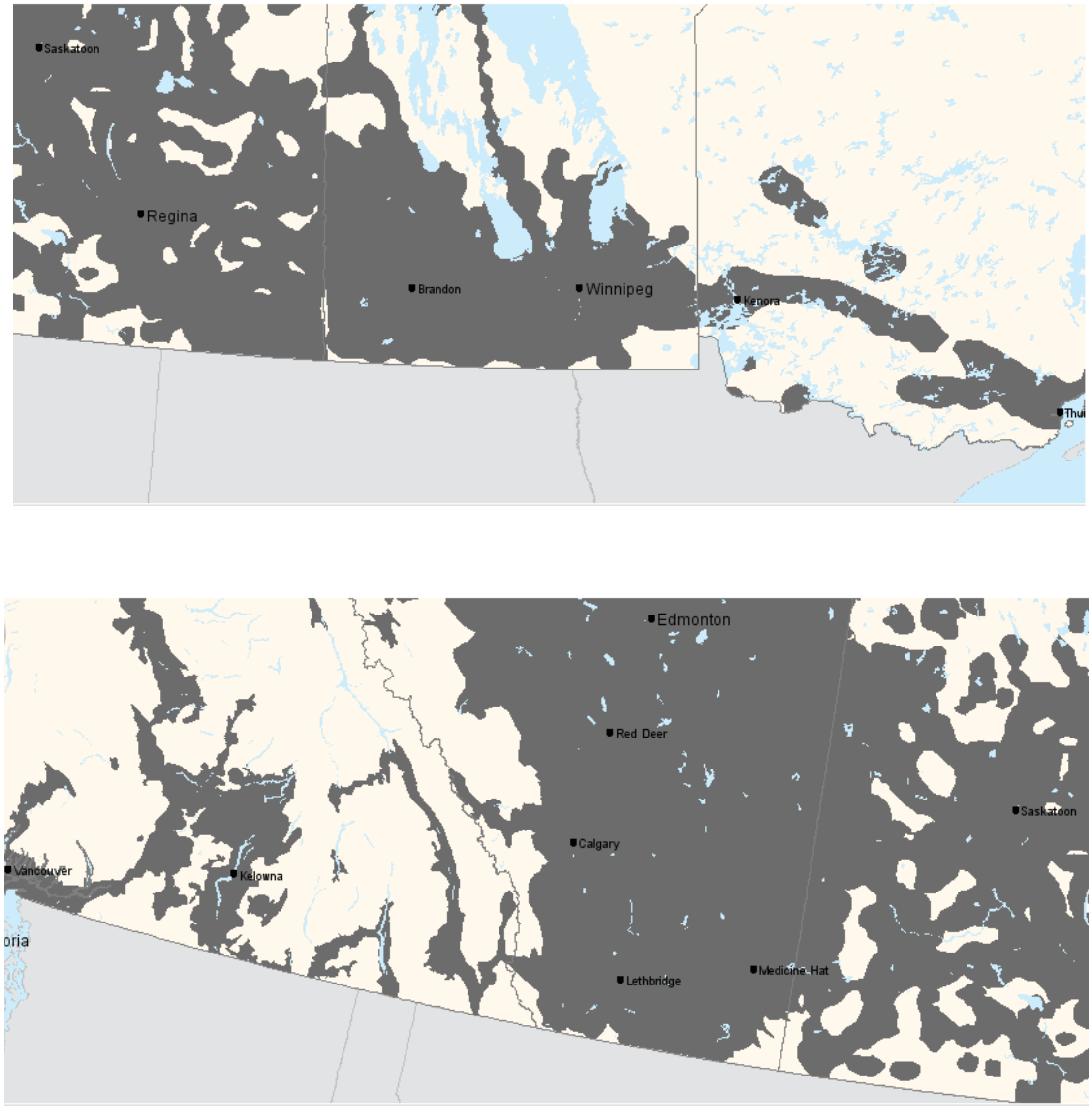

Figure 7   Bell Mobility 1xRTT Prairies coverage [6]

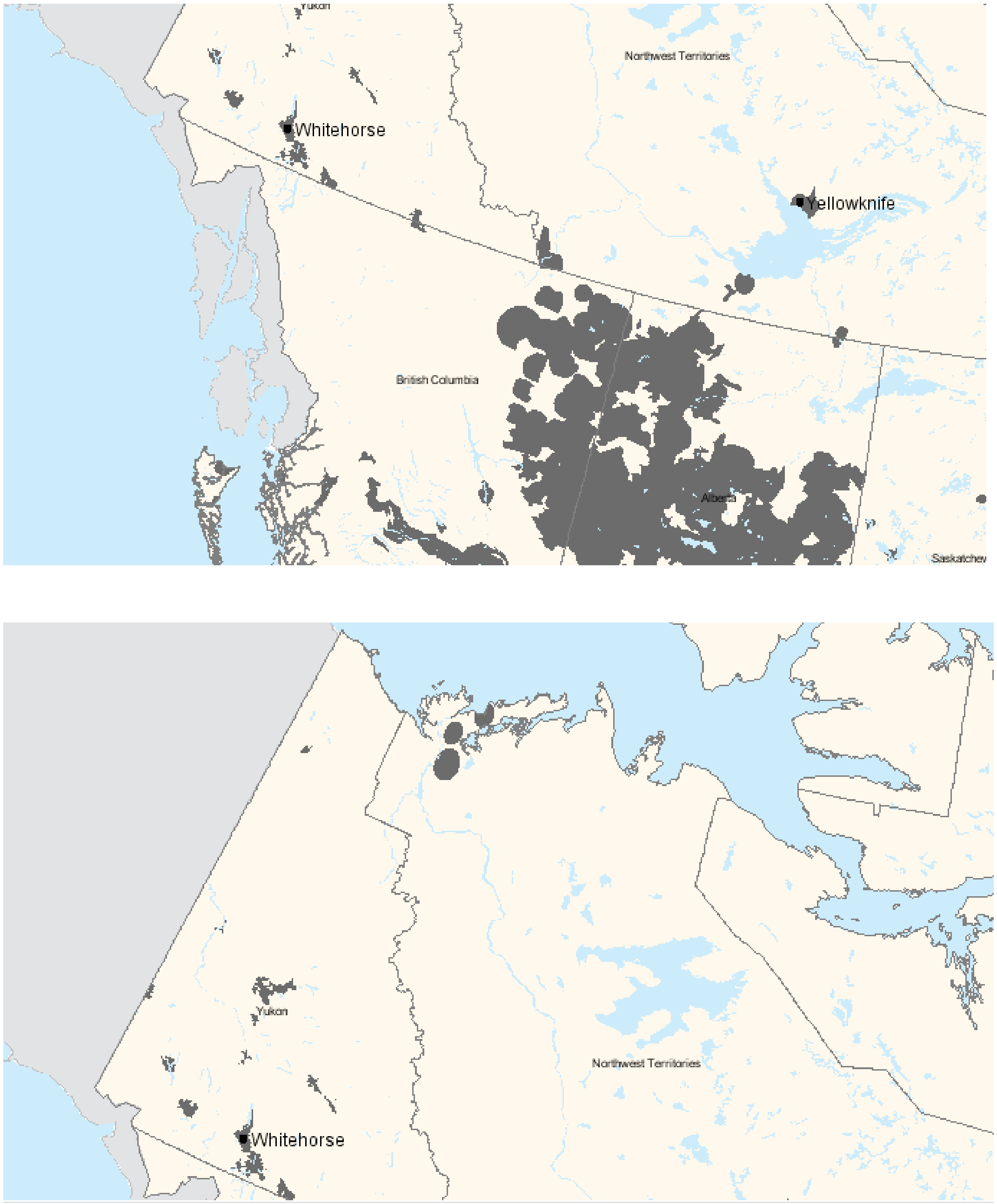

Figure 8: Bell Mobility 1xRTT Northern Coverage Map [6].

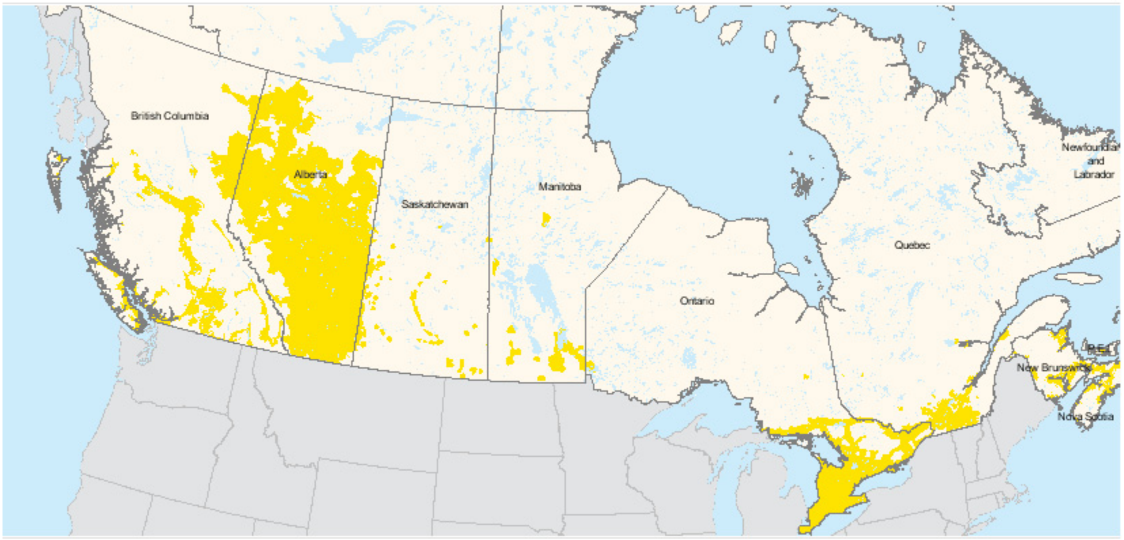

Figure 9: Bell Mobility 1xEV-DO Coverage Map [6].

6.3.2 Utility / Private Networks

Another option for public safety organizations to extend their radio coverage is to partner with utility and private networks, such as hydro, public works, forest logging companies, radio and television broadcasters, or wireless internet providers. Municipal, provincial and federal systems could also be shared.

Sharing radio systems can results in significant cost savings. The main drawback however is the potential disparity of the various networks, making interoperability very difficult. The security aspect as discussed above is another aspect to consider when using private networks. Solutions such as Software Defined Radios, to be covered later in this report, could address these drawbacks. Sharing only the tower infrastructure, and not the complete communications system as was discussed in 6.1.1, could be a more viable option.

6.4 Satellite Networks

Satellite communications is the most robust communications system for public safety operations. When telephone and broadcast networks go down due to major disasters such as flood, fire or explosions, satellite remain operational. Satellites also provide a quasi-ubiquitous coverage, not dependent on the business model of the terrestrial network operators. Satellite signals can reach any area on the earth. The actual coverage depends on the characteristics of the satellite system and ground terminals being used.

6.4.1 Satellite Network classification

There exist basically two main types of satellite networks, defined by the orbital plane in which the satellites are positioned.

- Geostationary (GEO) satellites are located 36,000 km above the earth, in a fixed position with respect to a point on the earth. Each GEO satellite can cover approximately one third of the globe within 75^o north and 75^o south. They support broadband communications, including voice, video and data applications, up to 6 Mbps bi-directional from portable terminal. Over 300 commercial GEO satellites are currently in orbit around the globe, operated by global, regional and national satellite carriers. In Canada, Telesat operates the Anik series, with Anik F2 offering two-way broadband multi-media services.

One potential problem with such an option is that their link budget is limited, which prevents their usage in situations where the satellites are not in direct line of sight from the terminal. In mountainous terrains and deep valley locations, such as in the Rockies, this prevents the use of that solution for coverage extension. In this case, a combination of a terminal positioned to have direct line of site with the satellite orbit, and a local mesh or ad hoc network, could be a solution (see Section 8.1.4). Temporary bases stations, as discussed in Section 6.2, could also be used in conjunction with the line of sight terminal.

- Low Earth Orbit (LEO) satellite operate between 750 km and 1500km above the earth surface, and provide voice and low speed data services (up to 512kbps). The satellites being closer to the earth allows to have smaller terminals. Depending on the orbit inclination and on the number of satellites in the constellation, global earth coverage can be achieved.

6.4.2 Potential Satellite Services

A number of satellite service providers offer mobile satellite services in Canada. The prominent ones are:

- Roadpost [8], using the Iridium constellation [9] or the Inmarsat satellites [10];
- GMPCS [11], also using Iridium and Inmarsat, as well as Globalstar [12].

6.4.2.1 Iridium System

The Iridium system is a constellation of 66 LEO satellites, interconnected via intersatellite links, and providing global coverage, including the north and south poles. Iridium provides voice, SMS and low data rate service (up to 2.4kbps) via a handheld radio (Figure 10).

Figure 10 Iridium phone

Iridium NEXT, the second-generation of the constellation, scheduled for early deployment in 2015, will provide L-band data speeds of up to 1.5 Mbps and high-speed Ka-Band service of up to 8 Mbps. For the higher data rates, conventional modems with satellite dishes will be required.

Roadpost offers monthly subscription to the Iridium system at rates starting at $50/month.

6.4.2.2 Inmarsat

Inmarsat provides telephony and data services to users worldwide, via portable or mobile terminals through a set of eleven GEO satellites (Figure 11). Of interest to Canadians, in July 2009, Inmarsat completed the acquisition of a 19-per-cent stake in SkyWave Mobile Communications Inc. (headquartered in Ottawa), which in turn purchased the GlobalWave business from TransCore.

The BGAN (Broadband Global Access Network) terminal (right side of Figure 11), provides GPRS-type services at up to 492 kbit/s. The subscription cost to the Inmarsat system also starts at $50/month, from Roadpost. Voice calls are typically priced at $1/min.

Figure 11 Inmarsat phones - handheld and mobile

6.4.2.3 Globalstar

Figure 12 Globalstar phone

GlobalStar is a constellation of 48 LEO satellites, providing connectivity to the public switched telephone network and the Internet. Users are assigned a telephone number similar to the cellular or wired system. Due to their lower orbit inclination, the constellation limits connectivity to within +/- 70^0, which would cover the Alaska/Yukon border. However, along that border, the signal is much weaker and users may experience regular drop outs.

Most Globalstar providers have roaming agreements with local cellular operators, enabling the use of a cellular SIM card with a Globalstar handset, and vice versa. Globastar system offers data rates up to 9.6kbps. GSP-1700 Satellte Phone are priced at $499.00 CDN with unlimited airtime voice plan at $19.99 per month ($999 without a twelve month plan).

6.4.2.4 MSAT

MSAT is the first dedicated system in North America for mobile telephone, radio, facsimile, paging, position location, and data communications, for users on land, at sea, and in the air. Canada-based TMI, and American Mobile Satellite Corporation (AMSC), each own and operate identical and interoperable GEO satellites. Both provide complementary mobile services, and each provides backup and restoration capacity for the other. MSAT-1 operates at 106.5 degrees West longitude. AMSC-1 is at 101 degrees West. Coverage is therefore limited to the Americas (North of Fairbanks, Alaska, and as far South as Caracas, Venezuela, extending over 100 kilometers off the coast of North America).

Communications between the mobile users and the satellites are accomplished at L-band. The MSAT radio supports continent-wide group and private Push-to-Talk (PTT) communications, as well as two-way telephone calls and data transfer. Land Mobile and Maritime antenna options provide advanced satellite tracking capabilities, ensuring users can communicate regardless of where they are located.

The system is being replaced by the LightSquared system (see section 8.2.1)

Figure 13 MSAT phone

7.0 Emerging Technologies

In this chapter, advanced or emerging wireless technologies are reviewed, providing different alternatives to extend the radio coverage. Since the communication world is now essentially digital, a brief discussion on the Internet Protocol, and its usage to carry voice signals (the so-called VoIP), is included. This will lay the foundation for the following sub-sections on emerging wireless access technologies, which will all result in the use of VoIP to carry voice communications. Promising access technologies, such as 3GPP Long Term Evolution (LTE/LTE Advanced) or IEEE WiMax (802.16e/m) are first considered. Then, technologies for the physical implementation of the radios to enable low cost, adaptability, interoperability and range extension are covered. Those include Software Defined Radio (SDR) and Cognitive Radio (CR) technologies.

7.1 A Few Words on the Internet Protocol

Before focusing the discussion on access technologies, it is of interest to review the Internet Protocol Suite, and discuss how information, in particular voice, can be transported over an IP network.

The first important thing to realize is that the Internet Protocol (IP) *is not* “The Internet”. In simple words, the latter, which is also often referred to as the “World Wide Web” (WWW), “The Web”, “The Public Internet”, etc, is the result of integrating a multitude of networks, using a common protocol as a unifying technology, the “Internet Protocol”.

The Internet Protocol is just that: a communications protocol, i.e. a formal description of digital message formats, and the rules for exchanging those messages in or between computing systems and in telecommunications. Protocols may include signaling, authentication and error detection and correction capabilities. A protocol describes the syntax, semantics, and synchronization of communication and may be implemented in hardware or software, or both. The Internet Protocol Suite is a series of communications protocols used in The Internet and other similar networks. It is commonly also known as TCP/IP, named from two of the most important protocols in it, the Transmission Control Protocol (TCP) and the Internet Protocol (IP).

It is therefore important to keep this distinction in mind when discussing the modern way of transporting voice information, the so-called “Voice over IP”, or VoIP. In digital networks, voice, after having been sampled and digitized, is transported in “frames”, or small packets of bits. This is not a new way of doing things in voice networks, and its use is not limited to the internet or the Internet Protocol. Digitization and packetization of voice signals have been used for years in the core Public Switched Telephone Networks (PSTN), in Local Area Networks (LAN) and Wide Area Networks (WAN). VoIP is merely another method to transport voice packets over a network. The quality of the VoIP transmission is a function of the voice compression algorithm, of the network implementation, and of the computing capability of the end-user equipment.

VoIP can be used (and is used) in private networks, such as Public Safety Project25 networks (e.g. in the Inter-System Interface – ISI, where IP is the protocol used to connect RF sub-systems), in commercial carrier networks (Rogers, Bell, Telus, Videotron, …), and over the Public Internet (Skype and the likes).

Over a private network, such as a P25 network, or even over the core of commercial carrier networks, the quality of the voice transmission (and of any data transmission) is directly related to the network implementation and architecture, and to the priority associated to the different types of data packets being transported. Voice and data transmissions can therefore be highly reliable, with high quality, even if the Internet Protocol and commercial networks are used. With VoIP, meeting the stringent Public Safety standards for voice quality and reliability is essentially a question of communications prioritization, not a question of technology (assuming all other things being equivalent, like radio bands, handset and equipment quality, transmission power, …).

The Internet Protocol is a packet-switched (PS) standard, as opposed to the circuit-switched (CS) standard that has been used for years in the PSTN. The packets (data or voice) are routed across the network according to the TCP/IP standard, which includes many variants to accommodate different traffic types. Voice being a “real-time” service, it must be treated differently than web browsing. With a combination of the Real Time Protocol (RTP) at the application layer, the User Datagram Protocol (UDP) at the network layer, and traffic scheduling via the use of Quality of Service (QoS) policies, VoIP communications can be made fully reliable. This is especially true on a private or dedicated network, where extra capacity can be built to avoid, or reduce to a minimum, packet delays, drops or contention. The new digital P25 networks being currently implemented are good examples of private networks, where the digital information (voice and data) is transported via IP routing, but where the dedicated resources, and the available capacity, provide adequate voice communications. At time of emergencies, a similar quality of service could be obtained from a commercial VoIP network, by dedicating most, if not all, of the local network resources (in the vicinity of the emergency site) to public safety communications, and/or by using proper access and traffic scheduling policies.

7.2 Commercial Wireless Access Technologies

As discussed previously, the coverage gap problem identified in the course of this study is essentially a wireless access (or lack of) issue. The previous section addressed the coverage extension from an infrastructure point of view. In this section, we approach the problem from the communications protocol, or how can the various infrastructures be accessed. Standard organizations (ITU, 3GPP/2, IEEE, …) are constantly evolving their communications protocols, to respond to the increasing needs of supporting more mobile users, each with more bandwidth demands for modern broadband applications. The emerging technologies aimed at addressing the so-called “4G” requirements are expected to provide a comprehensive and secure all-IP based mobile broadband solution to smartphones, laptop computers and other mobile devices. These emerging technologies, like the current commercial cellular networks, can be used to extend or supplement the current Public Safety radio coverage for both high quality voice and real-time broadband data simultaneously.

7.2.1 3G+ Networks

Wireless carriers have been rolling out for some time their third generation (3G) networks, capable of supporting voice, mobile internet and video calls in a mobile environment. Those 3G networks usually supports data rate up to 200 kbps. The newer deployed networks, denoted as 3.5G or 3G+ networks, carry even higher data rates, up to 14 Mbps, and are based on protocols such as 3GPP/HSPA+, CDMA2000/EV-DO, 3GPP/LTE, and Mobile Wimax. Those protocols lay the foundations for ubiquitous broadband wireless communications, which are to culminate in a few years to the fourth generation (4G), which promises to support data rates up to 1 Gbps.

3GPP/HSPA+ and CDMA2000/EV-DO Rev.B are CDMA-based technologies, extending GSM/EDGE and CDMA2000/1xRTT respectively. They are packet-switched protocols for data transmission usage, which are embedded and interoperate with a circuit-switched protocol that is used to carry circuit-switched voice and data transmissions. Theoretical peak rates can be in the few tens of Mbps in the downlink, and 10-20 Mbps in the uplink, depending on the RF bandwidth, and the antenna system configuration. The Medium Access Control (MAC) is partly performed at the physical layer (at the base station), allowing scheduling on short time intervals (e.g. 2msec in HSPA) and fast adaptation to mobile channel variations (thereby reducing the network latency).

3GPP/LTE and Mobile WiMAX (IEEE 802.16e) are based on frequency division multiple access (FDMA), such as orthogonal FDMA (OFDMA) and Single-carrier FDMA (SC-FDMA). The departure from CDMA techniques allows a better match with MIMO antenna technologies, as well as scheduling in the frequency and time dimensions. These characteristics, coupled with a short transmission time interval and larger RF bandwidths, pave the way to all-IP wireless networks, which is one of the 4G requirements. In a 20 MHz bandwidth, theoretical peak rates of 100 Mbps or more in the downlink, and 50 Mbps or more in the uplink are targeted (depending on the MIMO techniques used).

The International Telecommunication Union (ITU) has initiated the process of developing ITU-R Recommendations for the terrestrial components of the 4G IMT-Advanced radio interface(s). Some of the IMT-Advanced cellular system requirements are [13], [14]:

- Based on an all-IP packet switched network,
- Peak data rates of up to approximately 100 Mbit/s for high mobility such as mobile access, and up to approximately 1 Gbit/s for low mobility such as nomadic/local wireless access,
- Dynamically share and utilize the network resources to support more simultaneous users per cell,
- Scalable channel bandwidth, between 5 and 20 MHz, optionally up to 40 MHz,
- Peak link spectral efficiency of 15 bit/s/Hz in the downlink, and 6.75 bit/s/Hz in the uplink (using 4x4 and 2x4 MIMO respectively). This is similar to 3GPP/LTE,
- Smooth handovers across heterogeneous networks,
- Ability to offer high quality of service for next generation multimedia support.

Two emerging terrestrial standards are being designed around the IMT-Advanced requirements: the 3GPP Long Term Evolution (LTE) -Advanced, and the IEEE 802.16m (also known as Mobile WiMAX for "Worldwide Interoperability for Microwave Access"). The goal is to extend the capabilities of their respective current incarnation, but remain backward compatible with the deployed 3.5G networks, to meet the IMT-Advanced requirements. The relationship between the capabilities of IMT-Advanced and IMT-2000 (3GPP/HSPA and CDMA2000/EV-DO) is illustrated in Figure 14.

The standards are expected to be stable in 2011. Their application in commercial networks may have to wait a few years, in order to allow the wireless carriers to make their investment in 3G networks profitable.

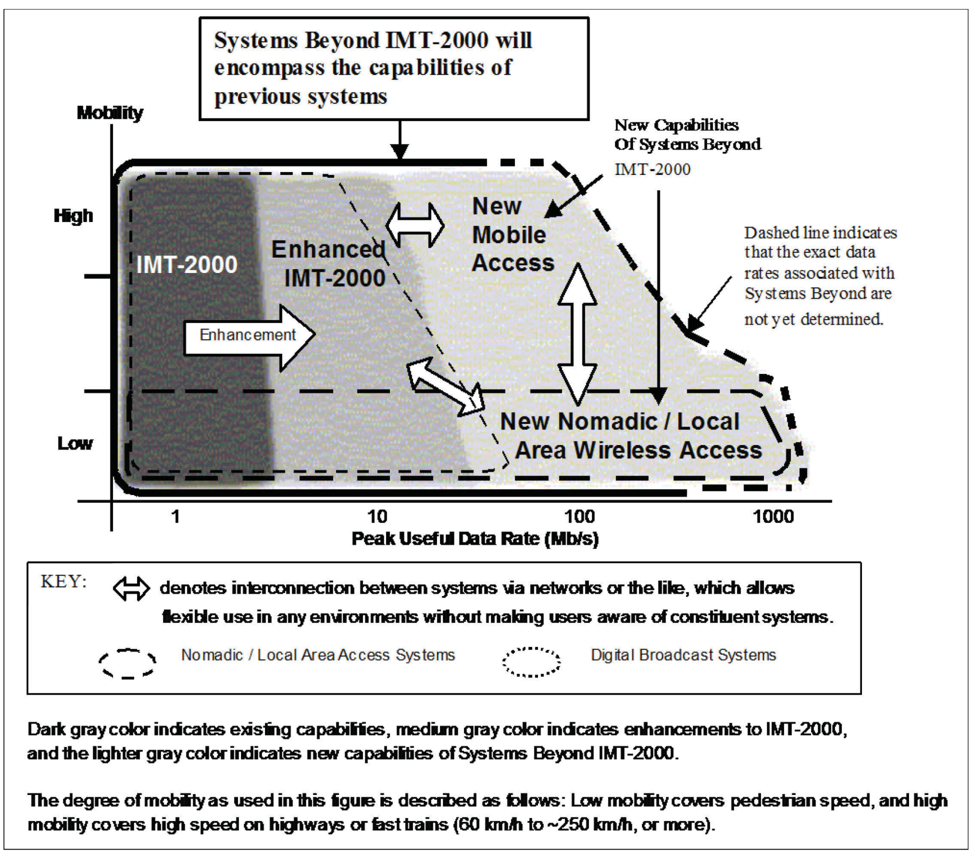

Figure 14: Illustration of capabilities of IMT-2000 and IMT-Advanced [13].

7.2.2 Unlicensed Mobile Access

Unlicensed Mobile Access or UMA, is the commercial name used by mobile carriers for external IP access into their core networks [15]. This access technique, available on a number of commercial handset and supported by multiple service providers, provides access to GSM and GPRS mobile services over unlicensed spectrum technologies, including Bluetooth and 802.11. By deploying UMA technology, service providers can enable subscribers to roam and handover between cellular networks, and public and private unlicensed wireless networks, using dual-mode mobile handsets.

This network access approach could be used in conjunction with a number of coverage extension techniques described in sections 6.2 and 8.1. A short range broadband WiFi network, constraint to the incident site, could be setup and linked back to the 3G+ mobile network.

7.3 Software Defined Radio

There are several definitions for software defined radio. The Wireless Innovation Forum [16] (former SDR Forum) defines Software Defined Radio as "*a collection of hardware and software technologies that enable reconfigurable system architectures for wireless networks and user terminals. SDR provides an efficient and comparatively inexpensive solution to the problem of building multi-mode, multi-band, multi-functional wireless devices that can be enhanced using software upgrades. SDR-enabled devices (e.g., handhelds) and equipment (e.g., wireless network infrastructure) can be dynamically programmed in software to reconfigure the characteristics of equipment. In other words, the same piece of 'hardware' can be modified to perform different functions at different times. This allows manufacturers to concentrate development efforts on a common hardware platform. Similarly, it permits network operators to differentiate their service offerings without having to support a myriad of handhelds. Finally, SDR provides the user with a single piece of scalable hardware that is at once compatible at a global scale and robust enough to deliver a 'pay as you go' feature set*."

Ideally, a software defined radio provides a variety of modulation techniques, wideband or narrowband operation, communications security functions (such as hopping) and waveform requirements of current and evolving standards over a broad frequency range. Programmability may extend to the entire system (e.g., with analog conversion only at the antenna, speaker and microphones) and allow first responders to affiliate seamlessly with the existing heterogeneous network infrastructures.

7.3.1 Description

In conventional radio design, a hardware chain such as that shown in Figure 15 is the standard design approach, typically with one chain for each waveform or communication protocol. Every section of both the transmission (modulation) and reception (demodulation) chain is completed in hardware. The demodulation section is often implemented as an Application Specific Integrated Circuit (ASIC), to reduce size and streamline manufacturing of the radios. A combination of Digital Signal Processors (DSP) and FPGAs can also be used for the baseband processing. Each hardware component of each radio chain section performs a specific radio function. Conventional radios with two or more waveform functions are often multiple transceiver chains placed together in the same device. Each chain uses its own hardware components and ASICs with their specific functions. Highly integrated ASIC could contain multiple waveforms. Most of the commercial cellular handset are designed this way, with highly integrated transceiver chains. Software programmability is performed at the network level (call set-up functions) and application level.

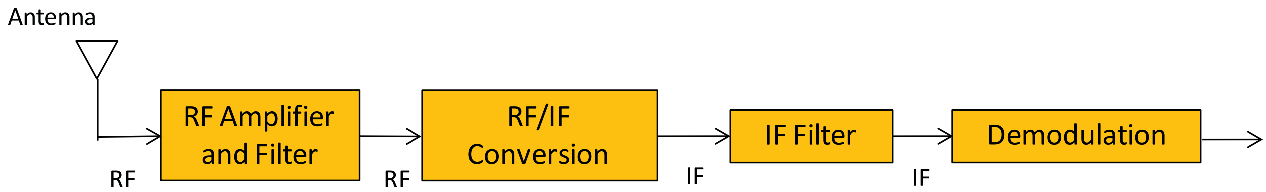

Figure 15: Conventional Radio Design (receiver).

Software Defined Radio can be defined as a wireless system in which some or all of the baseband and RF signal processing is performed in the digital domain. The physical layer of the protocol, responsible for frequency filtering, channel selection, modulation/demodulation, error correction, is processed in the digital domain using processors (e.g. General Purpose Processor (GPP) such as Pentium or PowerPC, DSP, and FPGA). The operating functionalities (operating frequency, modulation format, bandwidth, power) can thus be changed or augmented post-manufacturing, via software. There are no ASICs in SDR, as ASICs are by definition application specific and not reprogrammable. As shown in Figure 16, in an SDR, the goal is to bring the analog-to-digital conversion as close as possible to the radio antenna, such that as many radio functions as possible can be performed in software.

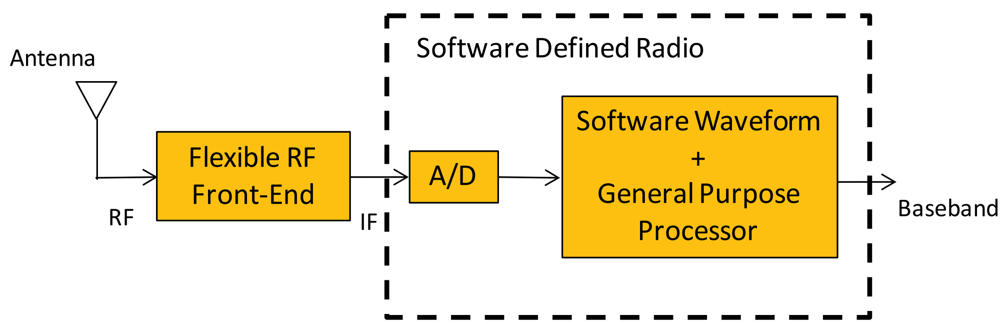

Figure 16: Software Defined Radio Design (receiver).

Software Defined Radios are ideally suited to multi-protocol radios, since they can allow configurability and upgradability via software, as well as the implementation of protocols running concurrently (with the proper signal processing power). Another advantage of SDRs is that the hardware can be made generic, and can be applied to many different protocols. By properly choosing the SDR hardware architecture, a radio upgrade path can be defined for many years. As the protocols become more complex and support higher data rates, and processor chips becomes more faster, the radio hardware can be upgraded with faster processors by changing processor boards while remaining backward compatible with previously written software (similar to the personal computers). This would eliminate the need to purchase a completely new radio unit.

7.3.2 Software Architecture

To operate the software defined radio, an architecture is required to enable the communication platform to load applications (e.g. waveforms), run these applications, and be networked into an integrated system. Most companies claiming to offer SDR products will use a proprietary architecture developed internally. While the radios can be qualified of SDR, they can only be reprogrammed and upgraded by the company, therefore locking the end-user to a single manufacturer, on a specific system.

Military organizations, around the world, are working on standardizing such an architecture in a non-proprietary model to create an eco-system of hardware and software vendors, promising to lower the acquisition cost, reducing the time-to-market of new functionalities and enabling higher level of interoperability, by facilitating software portability between platforms. One of the open-architecture being developed is referred to as the Software Communications Architecture (SCA). It is an open architecture framework that defines how elements of hardware and software are to operate in harmony within a software defined radio [17]. It has been initially developed by the US Department of Defence (DoD) to replace 750,000 tactical radios grouped in 25 to 30 families of radio systems — many of which could not communicate with each other — with software-based radios that could operate across the entire radio frequency spectrum from 2MHz to 2GHz. The international community, mainly through the Wireless Innovation Forum, has since heavily contributed to improve the original specification.

The SCA introduces the concept of Component Based Development (CBD) to the radio world. CBD promotes the use of independent software components that are assembled together to create an application. Instead of creating a program with tens of thousands of lines of program code tightly integrated, CBD suggests to assemble multiple interchangeable small modules (filter, modulator, demodulator, error correction, squelch detection, power control, …) into an application. Each module could be reused in different application, thus reducing the development time and cost, and allowing the best modules to be selected. Figure 17 shows a simplified design of a P25 transmitter using the CBD concept. Each of the boxes are coded individually, based on the SCA specification rules, and assembled to create the desired protocol. Software reuse is therefore greatly facilitated, as is insertion of new and improved implementations. Note that in Figure 17, only voice ports are shown for simplicity of the diagram. In most cases, a data port would also be included.

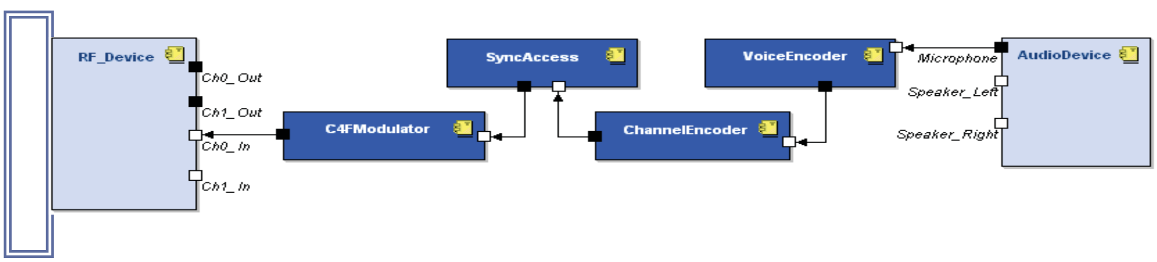

Figure 17 CBD simplified design of a P25 radio

The CBD architecture concept enabled by the SCA is shown in Figure 18. The aim of this architecture is to isolate the software radio applications from the radio hardware components via a communications middleware (standardized on CORBA) and a series of standard Applications Programming Interfaces (APIs). The software should execute mainly on a GPP using the functionalities of an Operating System based on POSIX (portable operating system instruction set), to facilitate portability of the software from platform to platform. In some instances, when power consumption or processing speed are critical, DSPs or FPGAs may be used. The Core Framework provides the management functionalities of the radio and is responsible to load, configure, start, stop and unload the software.

As can be seen, because of the inherent isolation between the application and the hardware, modifications to either ones is much easier to perform, enabling simpler and cheaper upgrades.

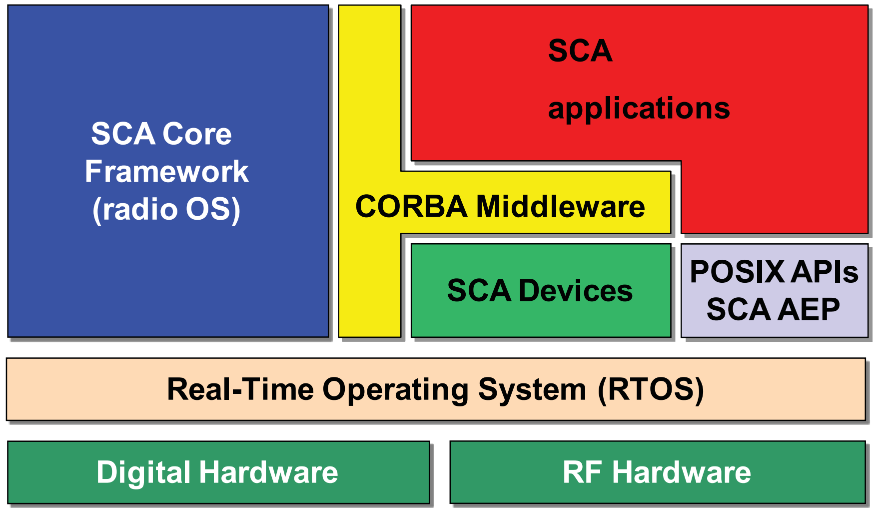

Figure 18: SDR – Component Based Development Architecture Error! Reference source not found..

SDR and SCA technologies can help to improve interoperability among public safety agencies, by providing the ability to tie together disparate systems, or provide flexible capabilities that facilitate radio access to multiple systems. Some of the key features of SDR/SCA technology are:

- **Reconfigurability**, by allowing the co-existence of multiple software modules implementing different standards on the same system. Within the SCA framework, the system can be dynamically reconfigured by selecting the appropriate software module to run. This dynamic configuration is possible in handset as well as in infrastructure equipment. The SCA facilitates the implementation of future-proof, multi-service, multi-mode, multi-band, multi-standard terminals and infrastructure equipment.

- **Ubiquitous Connectivity**, by enabling the implementation and co-existence of multiple air interface standards as software modules. This could help realizing global roaming, by allowing the installation of new software-based air interfaces, or by using software implementations of legacy standards.

- **Solution Interoperability**, by using an open architecture radio system, like the SCA, to allow the seamless integration of innovative third-party applications on SDR-based handsets and infrastructure equipment.

Although they are still research topics, the adaptability and flexibility of SDR architectures, including mesh and multi-hop networks, provide a framework where networks and devices will have the capability to adapt to real-time conditions encountered in specific locations in the network. In particular, SDR radios technologies provide coverage flexibility, by allowing real-time reconfiguration. This enables the use of more robust waveforms (beyond the capabilities of the "normal" waveforms used for day-to-day operations) for critical situations when coverage extension is needed. When coverage is limited by insufficient link budget or excessive interference, flexible and scalable extension solutions can achieved through the capabilities offered by SDR and Cognitive Radio in both the radio and the network.

In addition, Software Defined Radios offer enhanced flexibility over a hardware radio, enabling a wider range of waveform parameters to be changed with more precision (such as modulation and coding). SDR and cognitive algorithms can be developed to optimize coverage versus data rate over a large set of constraints, accommodating both commercial and public safety users. Waveform bandwidths and frequency selections can be adjusted, based on information relevant to the situation, such as geo-location and the relative positions of the users.

Scalable coverage can also be extended through means external to the infrastructure, such as repeaters to retransmit signals received from the infrastructure to out-of-reach devices (see Section 6.1). SDR and Cognitive Radios are key enablers of flexibility for configuring operating frequencies of the repeaters, base stations, and portables to mitigate interference in these types of systems. This concept can be extended to the case where the radio flexibility afforded by SDR, and the intelligence provided by Cognitive Radios at the network level, adaptively configure ad-hoc mesh networks, using a group of radio subscribers to extend coverage beyond that of the infrastructure. This network extension approach would allow transmissions to be passed back and forth from the incident site, along a network of individual responder radios operating in peer-to-peer mode, to a radio which can communicate with the main radio system/network.

7.3.3 Commercial SDR offering

There are a number of commercial offerings of SDR solutions. Most public safety radios built today are said to be SDR, whether they are from Motorola, Harris, Kenwood, Daniel Electronics and others. However, all are based on proprietary architectures. While this ensures a certain level of quality and after-sale services, it certainly limits the options to what the manufacturer will offer and at the price tag it will be offered.

A number of generic system based on the SCA are being offered on the market. Figure 19, Figure 20 and Figure 21 show products from three Canadian vendors of generic SDR platforms.[18], [19], [20].

Figure 19 Lyrtech Small Form Factor

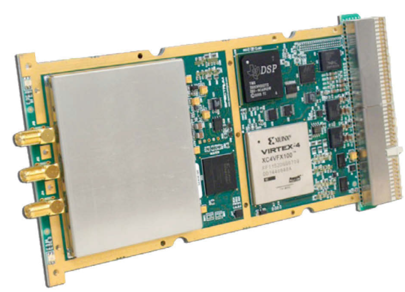

Figure 20 Spectrum Signal Processing SDR-4200

Figure 21 ISR Technology IDP-100

7.4 Cognitive Radio

While SDR can be seen as a paradigm shift in the design radios from hardware to software centric approaches, cognitive radio will be the next revolution in the use of the radios in an increasingly crowded spectrum environment.

7.4.1 Description

According to the Wireless Innovation Forum [21], [22], a cognitive radio is defined as:

"A radio in which communication systems are aware of their internal state and environment, such as location and utilization on RF frequency spectrum at that location. They can make decisions about their radio operating behavior, by mapping that information against predefined objectives. Cognitive radio is further defined as a device that automatically adjusts its behavior or operations to achieve desired objectives. The utilization of these elements is critical in allowing end-users to make optimal use of available frequency spectrum and wireless networks with a common set of radio hardware."

The Wireless Innovation Forum [22] also discusses the concept of *Intelligent Radio*, which is *a cognitive radio that is capable of machine learning*. This allows the cognitive radio to improve the ways in which it adapts to changes in performance and environment to better serve the needs of the end user.

One major application of intelligent and cognitive radio systems is the support of Dynamic Spectrum Access (DSA), in which the communication system selects the frequency spectrum where it will operate at a given location and over a given period of time, to optimize the use of available bandwidth and to avoid interference with other radios or other systems [22].

Based on an assessment of their operating environment, that may also include an evaluation of location identification information and any particular operating rule set, i.e. a "policy-based" rule set, cognitive radios can modify their operational parameters such as frequency, modulation schemes, and transmit power, in order to capitalize on available spectrum or other resources. A cognitive capability that can make real-time autonomous decisions for radio operations can increase spectrum efficiency, leading to higher bandwidth services as well as reduce the burdens of centralized spectrum management by public safety communications officials [23].

The Wireless Innovation Forum elaborates further on the architecture of cognitive radios [24]:

"There are two major subsystems in a cognitive radio; a cognitive unit that makes decisions based on various inputs, and a flexible SDR unit, whose operating software provides a range of possible operating modes. A separate spectrum sensing subsystem is also often included in the architectural of a cognitive radio, to measure the signal environment to determine the presence of other services or users. It is important to note that these subsystems do not necessarily define a single piece of equipment, but may instead incorporate components that are spread across an entire network. As a result, cognitive radio is often referred to as a cognitive radio system or a cognitive network.

The cognitive unit is further separated into two parts, as shown in Figure 22. The "cognitive engine" tries to find a solution or optimize a performance goal, based on inputs received defining the radio's current internal state and operating environment. The second engine is the "policy engine", and is used to ensure that the solution provided by the "cognitive engine" is in compliance with regulatory rules and other policies external to the radio."

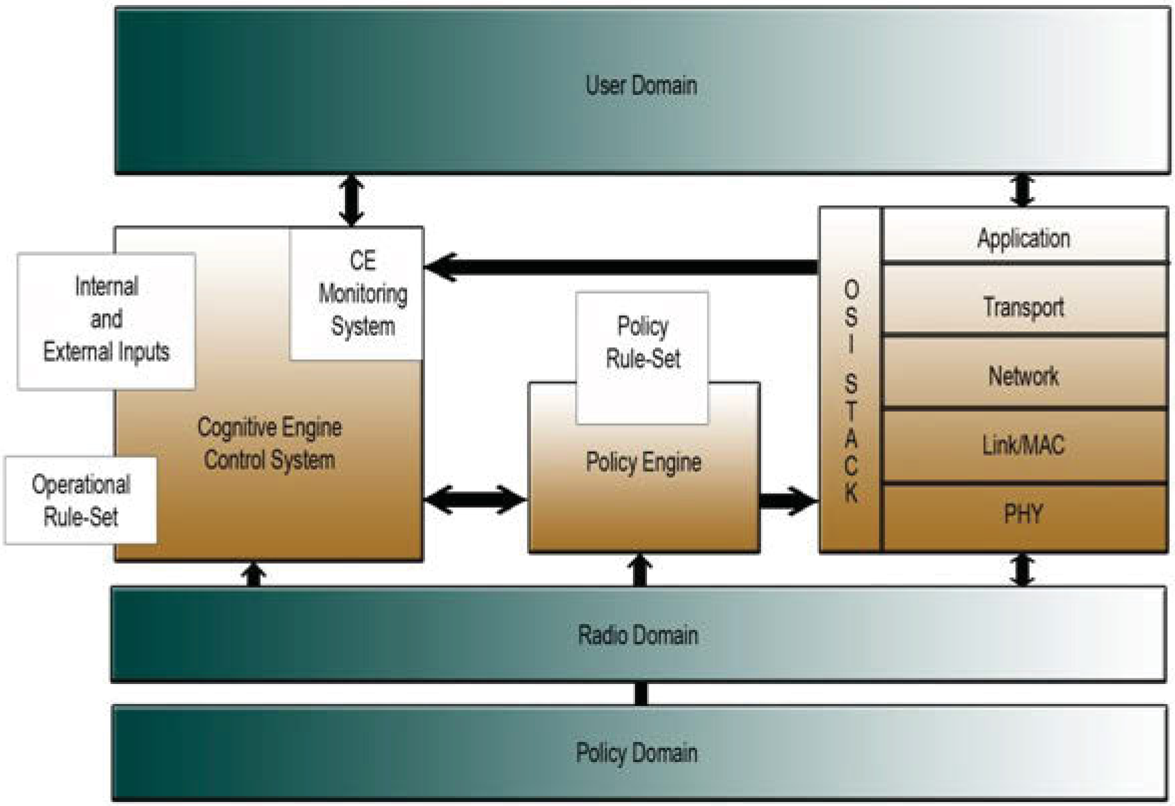

Figure 22: Cognitive Radio Concept Architecture [24]

7.4.2 CR applications

The cognitive radio concepts have numerous potential applications [25], [26], like:

- **Dynamic Spectrum Access (DSA)**, which is probably the most documented of these applications. In DSA, wireless devices dynamically adapt their spectrum access according to criteria such as policy constraints, spectrum availability, propagation environment, and application performance requirements. To realize DSA functions, cognitive radios or networks need information about their operating environment and governance on how to operate. Information required by a cognitive radio to implement DSA primarily refers to radio signal information, e.g., what signals are present in its environment, where are the signals emanating from, or where are the signals being transmitted to.

- **Radio Resource Management (RRM) and Link Adaptation**. In RRM, strategies and algorithms are deployed for controlling parameters such as transmit power, channel allocation, data rates, handover criteria, modulation scheme, error coding scheme, etc. The objective is to utilize the limited radio spectrum resources and radio network infrastructure as efficiently as possible. Link Adaptation, which typically involves Adaptive Coding and Modulation (ACM) and Transmit Power Control, can be seen as being part of RRM. Cognitive radio techniques can be applied to RRM, to manage Quality of Service (QoS) and fairness, to reduce interference, to perform RRM across multiple wireless protocols, to select antenna system configurations (e.g. to choose between different MIMO schemes such as antenna diversity, spatial multiplexing, or beamforming), etc.

- **Spectrum Leasing**, where the radio intelligence would be used to automate and process the opportunistic leasing of spectrum by the minute or by the hour. This would allow primary users to dynamically resell spectrum to secondary users. Spectrum allocations would then be shifted with changing demands and would allow primary users to extract further value out of their spectrum when it is not fully utilized. Note that this feature could be of significant interest in cases where bandwidth, reserved to public safety organizations, gets used and managed by private operators for commercial use (cellular phones or internet access for example). Public safety would lease their bandwidth to third party but would reclaim it automatically if needed. Operator intervention would not be needed as a policy engine (e.g. based on the Public Safety Governance Model), inside the cognitive radios would automatically make the switch.

- **Radio Interoperability**, at different levels, such as adjusting traffic priority in real time as a function of events, resource demand, capacity, and users' roles; downloading a waveform and the ability for non-first responders' radios to be reconfigured accordingly; or reconfiguring the radio while responders are either en route to the incident, or in the field as needed when responders are reassigned. The PS CR could be designed with additional security features that would defeat terrorist attacks and jamming

Using the above features in a Cognitive Radio environment could greatly enhance public safety operations. This would enable the users to select the optimum frequency band to communicate their information. No need to try to fit everything in a single over-crowded band, or in remote areas, in a band without coverage. Cognitive radios will adapt to its environment as pictorially shown in Figure 23 to enable a much more efficient communications and spectrum use.

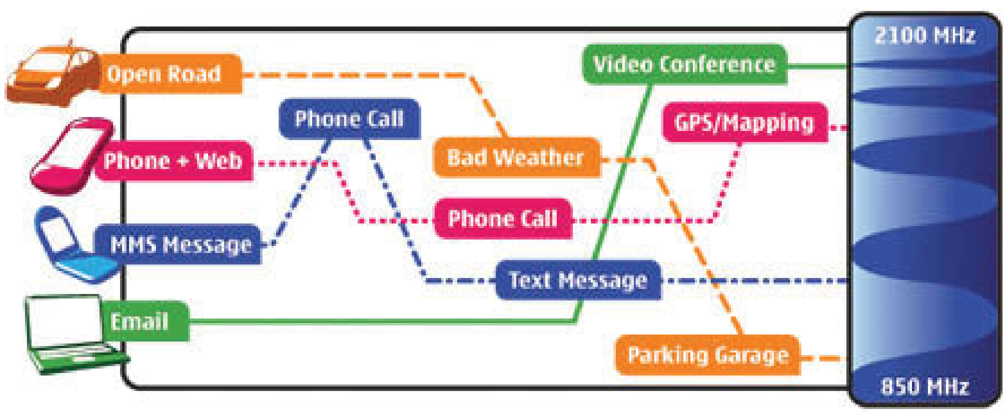

Figure 23 CR dynamically the spectrum usage to optimally transfer the information [27]

Cognitive radios, enabled by SDR technologies, could facilitate interoperability between communication systems by autonomously adapting to the needs and conditions of surrounding radios and network. In emergency situations, there is little time to setup networks or reconfigure the radio parameters to communicate. This technology could be used to extend the radio coverage, by detecting compatible radios and enabling peer-to-peer communications used in a relay to reach remote infrastructures. This concept will be covered in more details in section 8.1.4.

7.4.3 Commercial Offering

Apart from the above applications that are slowly being incorporated into radio sets, true Cognitive Radio is still in its infancy, with development being performed mainly at the research level. Barriers to implementation reside not only in the implementation of efficient cognitive engines and provision of low cost RF front-end capable of operating over multiple frequency bands, but also on the government frequency allocation rules. The US Federal Communications Commission (FCC) is touting with the concept in unlicensed band, but is very conservative to permit it in regulated bands. There is a large debate over the use of CR technologies in the newly open 700MHz band.

8.0 Coverage Extension Approaches using Emerging Technologies

In the previous section, emerging wireless technologies were presented from the access protocol point of view, and the benefits that such techniques could bring in terms of generic higher broadband connectivity. The all IP network, supported by the 4th generation cellular network protocols, were proposed to provide the capability to network the different radios in a broadband environment. SDR and cognitive radio technologies were described mainly as implementation approaches enabling spectrum efficiency and interoperability.

In practice, Public Safety personnel may face a broad spectrum of scenarios, with different degrees of uncertainty with respect to the communications requirements. In situations happening along the Canada-US border, it seems that the main shortcoming is the lack of radio coverage in less favorable terrains or regions. But the nature of Public Safety events is such that multiple organizations are often involved, and system interoperability is an issue that has also to be kept in mind.

In this section, those technologies are used to propose various approaches to extend the Public Safety radio communications coverage. It is assumed here that the first responders operate in areas where the tower is out of reach of their conventional public safety radios. Some specific state-of-the-art technologies will be discussed, with the aim of addressing the issues of:

- the integration of disparate wireless access technologies,
- the reconfigurability and adaptation of the communications equipment to changing situations,
- the optimization of the access resources, and
- the radio coverage extension in difficult terrains.

The section is divided into two sub-sections, the first one covering terrestrial-based approaches and the second section dealing with satellite based extensions.

8.1 Terrestrial Coverage Extension

In this subsection, various terrestrial-based approaches to extend the radio coverage are presented. We will not cover the simple case whereby first responders could simply revert to the commercial cellular system as this was covered in Section 6.3.

8.1.1 Multi-mode Radio (Commercial / Public Safety)

An obvious connectivity backup to the privately owned public safety networks is to use the commercial cellular infrastructure. In some instances, first responders extensively use the commercial network for their daily operations, mainly for broadband access that is unavailable on their narrow band system. In most cases however, first responders have to carry two sets of radios, one for the public safety network, and one for the commercial cellular one.

With the opening of the 700MHz band, resulting from the television digital dividend, there is a potential that radio manufacturers offer dual-mode radios capable of operating on both the public safety and commercial cellular networks. No decisions have yet been made but the authorities, and the operators are leaning towards the 4G LTE protocol. This would greatly simplify the design of the radios.

Nevertheless, first responders systems will continue to operate for some times to come in the other frequency bands reserved for them, namely 150MHz and 400 MHz. SDR technologies could be put to use to enable multi-mode radios.

8.1.2 Mini-base Stations based on Femtocell Technology

A femtocell is a small cellular base station, typically designed for use in a home or small business. It connects to the service provider's network via broadband (such as DSL or cable). Unlike hot spots, which assumed WiFi connectivity to the Internet at the user level, in this case, the users connect to the network using a dual band cellular phone (WiFi and cellular bands). Current femtocell station designs typically support 2 to 4 active mobile phones in a residential setting, and 8 to 16 active mobile phones in enterprise settings. Such a mini-base station allows service providers to extend service coverage indoors, especially where access would otherwise be limited or unavailable. Although much attention is focused on WCDMA (UMTS, HSPA), the concept is applicable to all standards, including GSM, CDMA2000, TD-SCDMA, WiMAX and LTE solutions.

In emergency situations occurring in remote areas, a femtocell mini-base station could be dropped to cover the emergency site. Terrestrial microwave or satellite backhauls would be required to close the loop with the central office. Figure 24 depicts a mini-base stations with backhaul connectivity via a satellite link.

Figure 24 Super Pico Cell from STM [28]

8.1.3 Distributed Access Network

Alcatel-Lucent recently announced the availability of a cellular access technology portfolio, *lightRadio*, based on the femtocell concept [29], but applicable to much larger territories than home or enterprise. They are aiming for city-size networks, the metro-femtocell. The lightRadio system has a flexible architecture that distributes intelligence throughout the network, so that it can dynamically expand to meet growing demands [30].

Figure 25 Alcatel-Lucent Lightcube antenna

The central and novel component of this technology is a small cube, invented by Bell Labs, which combines a wideband active array antenna with fully software defined radio capability (Figure 25). This cube weights less than 300 g and can be stacked to build an active array antenna, with an RF power going from 2 watts, to cover a local area network, to 60 watts, typical of cellular towers. In this architecture, the base station, typically located at the base of each cell tower, is broken into its component elements and distributed through the network or 'carrier cloud.' The baseband information is transferred to a centralized processing unit, using the Common Public Radio Interface (CPRI) compression technique (see Figure 26). This processing centralization, which could efficiently use Software Defined Radio technology (see Sub-Section 7.3), facilitates maintenance, network management, upgrades, etc. Additionally, in lightRadio, the various cell tower antennas are combined and shrunk into a single multi frequency, multi standard (2G, 3G, LTE) device that can be mounted on poles, sides of buildings or anywhere else there is power and a broadband connection.

For First Responder applications, such technology could be used to expand the network at much lower cost than that of building large tower infrastructures. Ultimately, such technology could be installed on hydro poles along the roadside. One has to be cautious however that the maintenance cost (repair and fixes) is often higher than the deployment cost. A distributed network may prove to be more expensive than a central "star" type network.

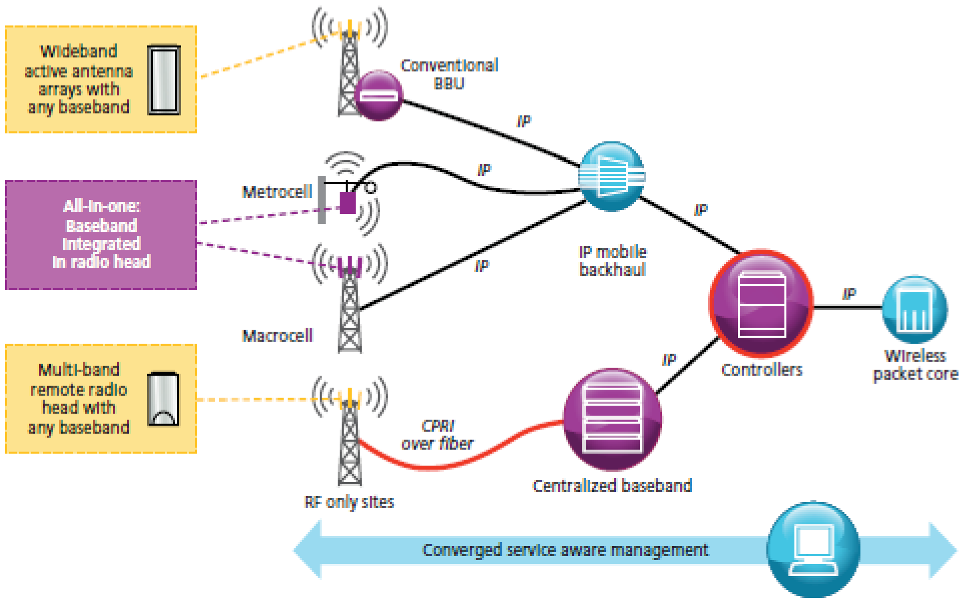

Figure 26: lightRadio architecture overview, with antennas, radios, baseband, controllers and management [31]

8.1.4 Peer-to-peer ad-hoc networking

Rather than relying on fixed terrestrial infrastructure as described above, Mobile Ad Hoc Networks (MANET) consists of a dynamic collection of nodes, with changing multi-hop topologies that are composed of wireless links as depicted in Figure 27. Such a network may be self-contained, or it may be connected to a larger network. MANETs have no underlying fixed infrastructure such as routers in wired networks or access points in managed (infrastructure) wireless networks.

MANETs can therefore provide a solution to quickly establish survivable, efficient, dynamic communication for emergency and rescue operations, disaster relief efforts, and military networks. Each mobile node act as wireless router and can relay information if needed. The selection of the forwarding nodes is made dynamically, based on the network connectivity. MANETs allow the coverage to be extended where WLAN coverage or wired networks are not available. The MANET technology allows network connections beyond line-of-sight (LOS) or beyond the capabilities of a single radio asset. They offer rapid deployment, self-configuration, dynamic reconfiguration or self-healing capabilities. Ad hoc networks, whether they are composed of stationary or mobile nodes, can be very useful when deployed in urban or complex terrain where obstacles block a direct link to a gateway.

Vehicular Ad-Hoc Network (VANET) is a subset of MANET, which supports data communications among nearby vehicles and between vehicles and nearby fixed infrastructure. Depending on the range of data communications, nodes in VANET communicate among themselves via short-range (vehicle-to-vehicle) or medium-range (vehicle-to-roadside) communications [32].

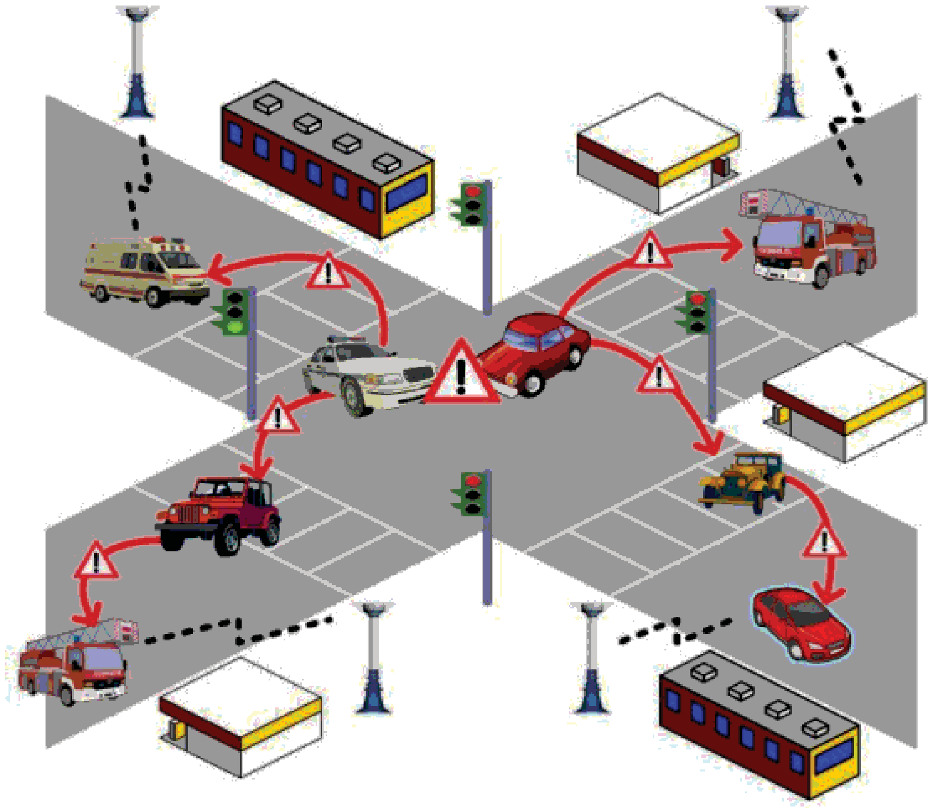

Figure 27: Vehicular ad hoc network [32]

The characteristics of such networks are summarized below:

- Self-forming, self-healing capabilities,
- Nodes act as relays,
- Extended coverage,
- Distributed system (sensor nodes - no single point of failure),
- Link redundancy for increased system reliability,
- Autonomous, no infrastructure needed,
- Energy constraint radios (battery operated),
- An ad-hoc network can be part of another network.

Mesh networks can be seen as one type of ad hoc network. MANET and mesh networks are therefore closely related. They also provide multi-hop relaying and support the self-healing capability. A wireless mesh network often has a more planned configuration, and may be deployed to provide dynamic and cost effective connectivity over a certain geographic area. Often the mesh routers are not limited in terms of resources compared to MANET nodes, and thus can be exploited to perform more resource intensive functions. In this way, the wireless mesh network differs from an ad-hoc network, since these nodes are often constrained by resources. Figure 28 shows an example of a mesh network.

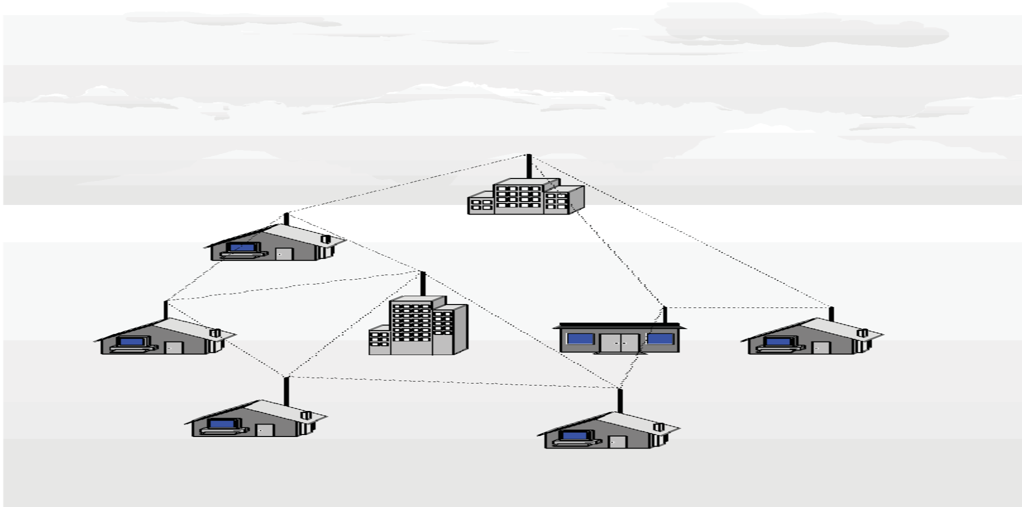

Figure 28: Mesh Network

Many companies offer mesh ad-hoc networking technologies. Motorola offers a series of product solutions to create robust mesh wide area networks (MWAN) [33]. For example, the AP 7181 is multi-radio 802.11n access point, offering a maximum data rate of 300 Mbps, and Motorola's ADEPT (ADvanced Element Panel Technology) antenna system (Figure 29). ITT also offers a mobile ad-hoc networking solution [33] that provides voice, integrated GPS with Situation awareness (SA) reporting, and data transfer (100 - 1500 kbps) across dismounted networks spanning 6 km. The ITT SpearNet system is claimed to maintain voice and data communications within difficult environments, such as tunnels, ship cargo holds, fast moving vehicles and buildings [34]. Figure 30 shows the ITT Spearnet vehicle mounted radio. A corresponding handheld unit also exists.

Figure 29 Motorola AP7181 MWAN antenna [34]

Figure 30 ITT Spearnet vehicle mounted radio [34]

8.2 Satellite Coverage Extension

The previous section described a number of new approaches to extend the coverage using terrestrial infrastructures. This section describes approaches that make use of new satellite systems that can be directly access from a handheld unit and yet can be made compatible with the terrestrial cellular network infrastructure. A number of satellite service providers are working on such systems, to provide ubiquitous access to high speed, secure and resilient satellite-terrestrial communications. Two organizations with projects of interest are LightSquared [35] and TerreStar [36].

8.2.1 LightSquared

LightSquared is planning to operate an integrated terrestrial wireless broadband and satellite network. The goal is to provide a cellular network for primary ground-based wireless connectivity, and to use satellite access connectivity to supplement the network in underserved areas (the satellite acting as a cell tower in the sky). The concept is based on the Canadian MSAT system launched in geostationary orbit in 1995 as the first dedicated system in North America for mobile telephone, radio, facsimile, paging, position location, and data communications for users on land, at sea, and in the air.

LightSquared is building a US nation-wide 3GPP/LTE terrestrial network, which will integrate with the services provided by the geostationary SkyTerra 1 satellite, launched in November 2010 and placed in geostationary orbit at 101.3 degree west (Figure 31). A second satellite, SkyTerra2, is planned to be launched later in 2011. The satellites will cover Canada, the United States, including Alaska, Hawaii, Puerto Rico, the Virgin Islands, Mexico and the Caribbean Basin (Figure 32). They will replace the MSAT 1 and 2 satellites. In addition to the commercial terrestrial cellular network service, LightSquared is also planning to offer handsets operating in the 700MHz public safety frequency band.

A large antenna reflector is used (22m) on the satellite to allow very narrow spot beams in the L-band (1.5/1.6 GHz). In term of dual cellular-satellite phones, the system uses the Qualcomm proprietary advanced satellite air interface technology called EGAL (Enhanced Geostationary Air Link), which enables the satellite mode of operation in mobile devices. Qualcomm is adding L-Band LTE and EGAL to standard Qualcomm products, including its MDM9600™ chipset. This will enable handset manufacturers to develop integrated cellular-satellite products that are similar to today's typical mobile devices, in terms of size, capabilities, and build costs. Nokia, AnyData and Bandrich have partnered with Lightsquared to provide branded data-centric products.

LightSquared business model is that of a wholesaler only, without any direct relationships with the end users. This will allow commercial partners to solely own the relationship with the end user. LightSquared is anticipating commercial launch in the second half of 2011 in the US. The network will provide nationwide services from its commercial launch date through satellite coverage and roaming partnerships, as it continues to extend its footprint.

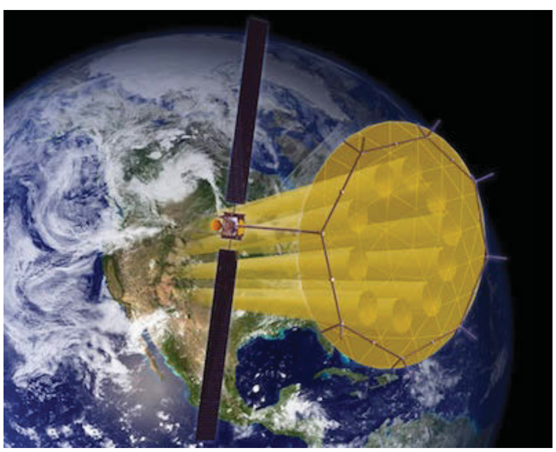

Figure 31 SkyTerra 1 satellite (artistic rendition)

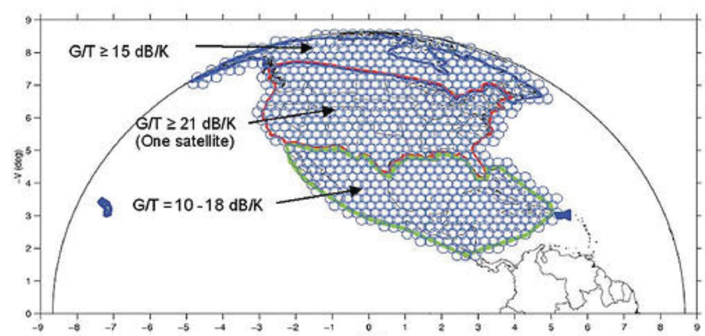

Figure 32 SkyTerra 1 coverage

8.2.2 TerreStar

Similar to LightSquared, TerreStar [36] operates an integrated satellite-cellular communications network. They have partnered with AT&T to take advantage of their 3GPP/HSPA and GSM/EDGE terrestrial network. The satellite component is provided by TerreStar-1, launched in July 2009 and uses the ETSI GMR-1 protocol, a 3G extension of GSM for satellite. The satellite is located at 111 degree West and provides coverage for the US using hundreds of beams in the S-band (2GHz). Table 1 provides the technical communications parameters of the system, and Figure 33 shows the conceptual system for an hybrid terrestrial cellular and satellite network.

Table 1 Protocol and Frequency plan for the Terrestar system

Satellite	
GMR-1 3G	2000 – 2010 MHz 2190 – 22200 MHz
Cellular	
WCDMA/HSDPA GSM/EDGE	850/1900 850/900/1800/1900

Figure 33 Terrestar conceptual system

Figure 34 maps the coverage areas and shows beams along the Canada-US border. The original plans (before the restructuration) were to also cover the whole of Canada [37]. Note that because the satellite is in Geostationary orbit, the system performance will degrade to the point of becoming nil, if direct line of sight to the satellite is not maintained, such as could happen in valleys and canyons.

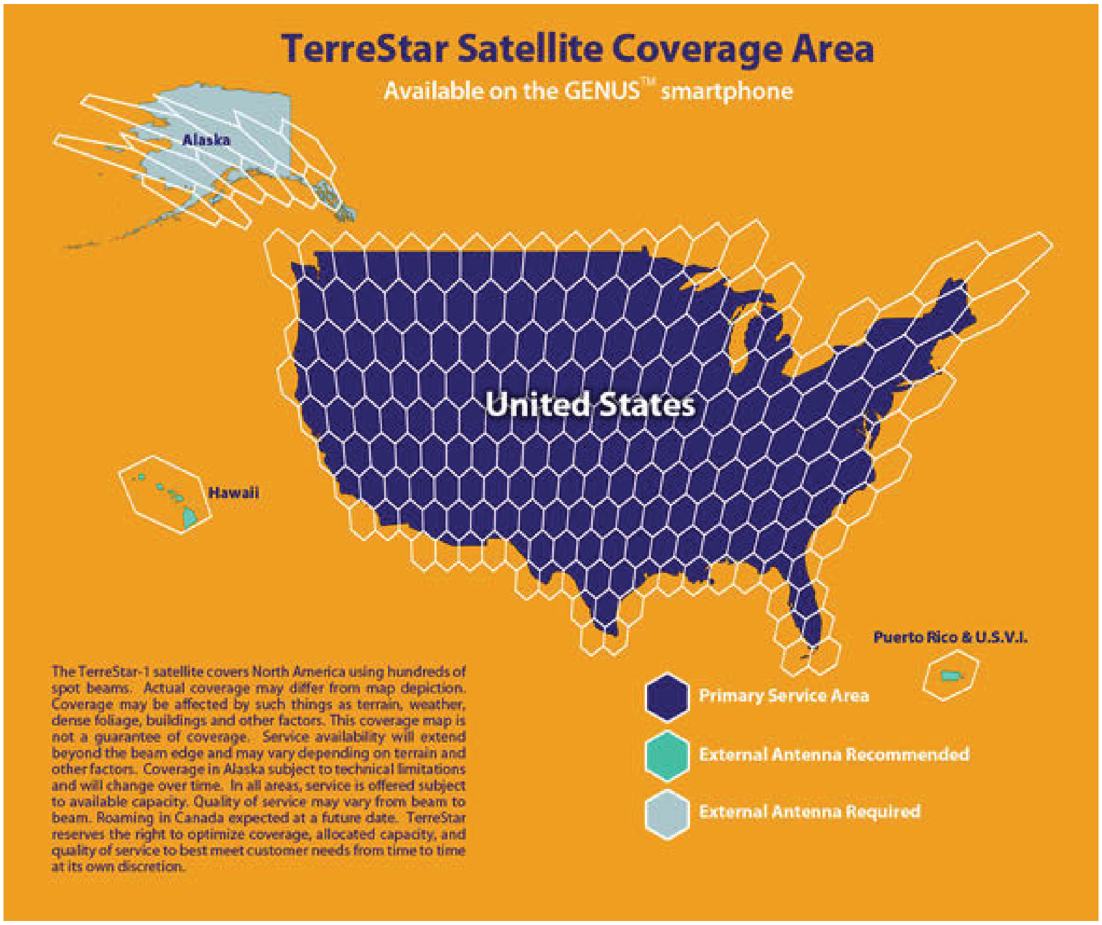

Figure 34 TerreStar-1 Satellite coverage area

In November 2010, TerreStar launched GENUS (Figure 35), a cellular-satellite smartphone, to take advantage of the AT&T's, and the GMR-1 3G satellite network.

Figure 35 Terrestar GENUS smartphone offered by AT&T

In October 2010, Terrestar filed for Chapter 11 bankruptcy to protect itself from liabilities in the range of $1.6 billion. EchoStar (the largest creditor) offered to provide interim funding during restructure, but talks have recently ended. Note that a decade ago, two other mobile satellite operators, Globalstar and Iridium, both sought Chapter 11 protection. As is the case with most Chapter 11 filers, Globalstar and Iridium emerged largely debt-free and have since built businesses that are now building their second-generation satellite constellations.

8.2.3 Public Safety Communications Satellite Gateway

The previous two sections considered an integrated terrestrial-satellite system, whereby the end user radio communicates directly with the satellite or terrestrial infrastructure. While this offers extreme autonomy and versatility, the data rate is often limited to a few hundred of kbps due to the limited power of the handset. In addition, the satellite bandwidth utilization is not optimized as each user is considered independently. In the case of major incidents where multiple responders need to converge on a remote area, such as a forest fire, flood, plane crash, a more coordinated approach servicing multiple users is required to provide higher data rates and bandwidth optimization.

Satellite gateways are potential solutions. The ground users communicate on some form of terrestrial ad-hoc networks composed of UMA, Femtocells, and even MANETS ending to the gateway, which aggregates the use traffic, prioritizes it, allocates proper bandwidth to each message and relay the information to the central office over an optimized satellite link. In the early 2000, Telesat, CRC, Canadian Space Agency and Simon Fraser university teamed to develop the REMSAT (Real-time Emergency Management via SATellite link). Figure 36 shows a conceptual diagram of the REMSAT™ system, capable of bridging satellite components (communications, remote sensing, geolocation) to terrestrial components (mobile and handset radios). Figure 37 shows the REMSAT deployable command centre. The system is still being used in British Columbia. Today, a number of companies are offering similar products.

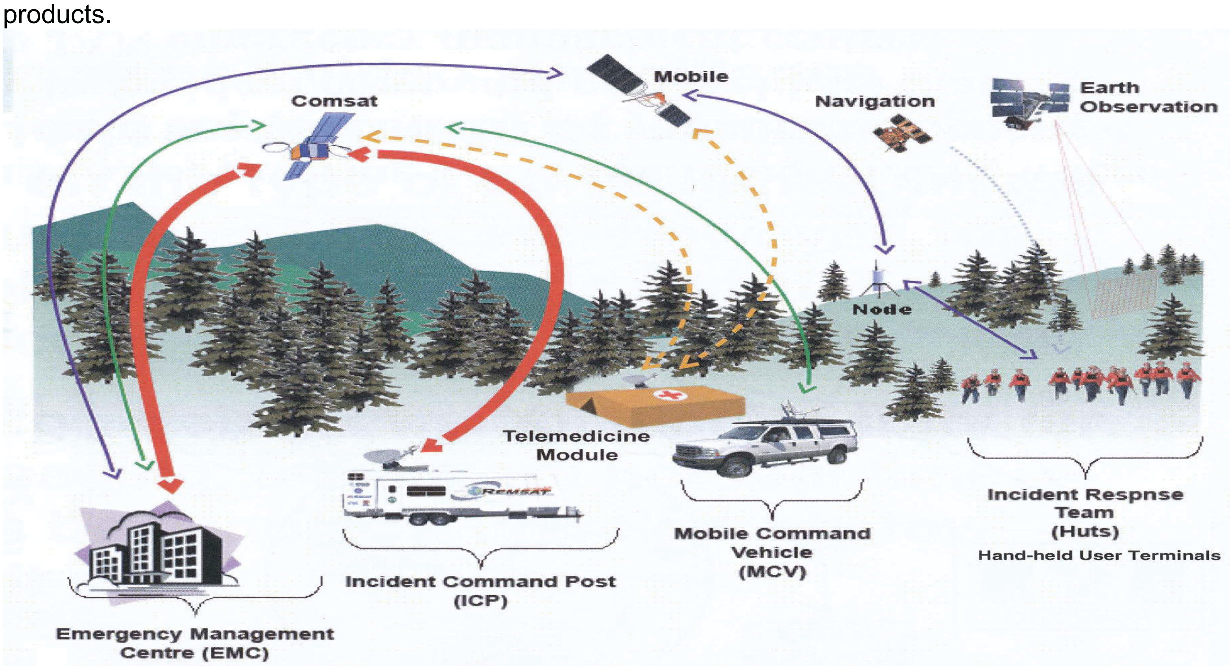

Figure 36 Conceptual diagram of the REMSAT™ system

Figure 37 REMSAT gateway and remote command centre

8.2.3.1 SDR base Satellite Gateway

The Public Safety Communications Gateway, as presented in this sub-section, is a concept being developed at CRC [38]. It uses SDR technologies to integrate a Public Safety P25 network with AM and FM handheld radios, cellular access, SARSAT distress beacons and a DVB-S/S2 satellite backhaul. The concept is illustrated in Figure 38 where the networks of mobile devices can be operated in conventional mode, as well as in a mesh configuration, to provide coverage extension. In this research project, the Communications Gateway integrates a software defined radio platform, with software waveform applications implementing the physical layer of the different supported access technologies. The overall radio controller supervises the mobile access, the resource management and the protocols interoperability, and cognitive radio principles will be integrated as the research progresses.

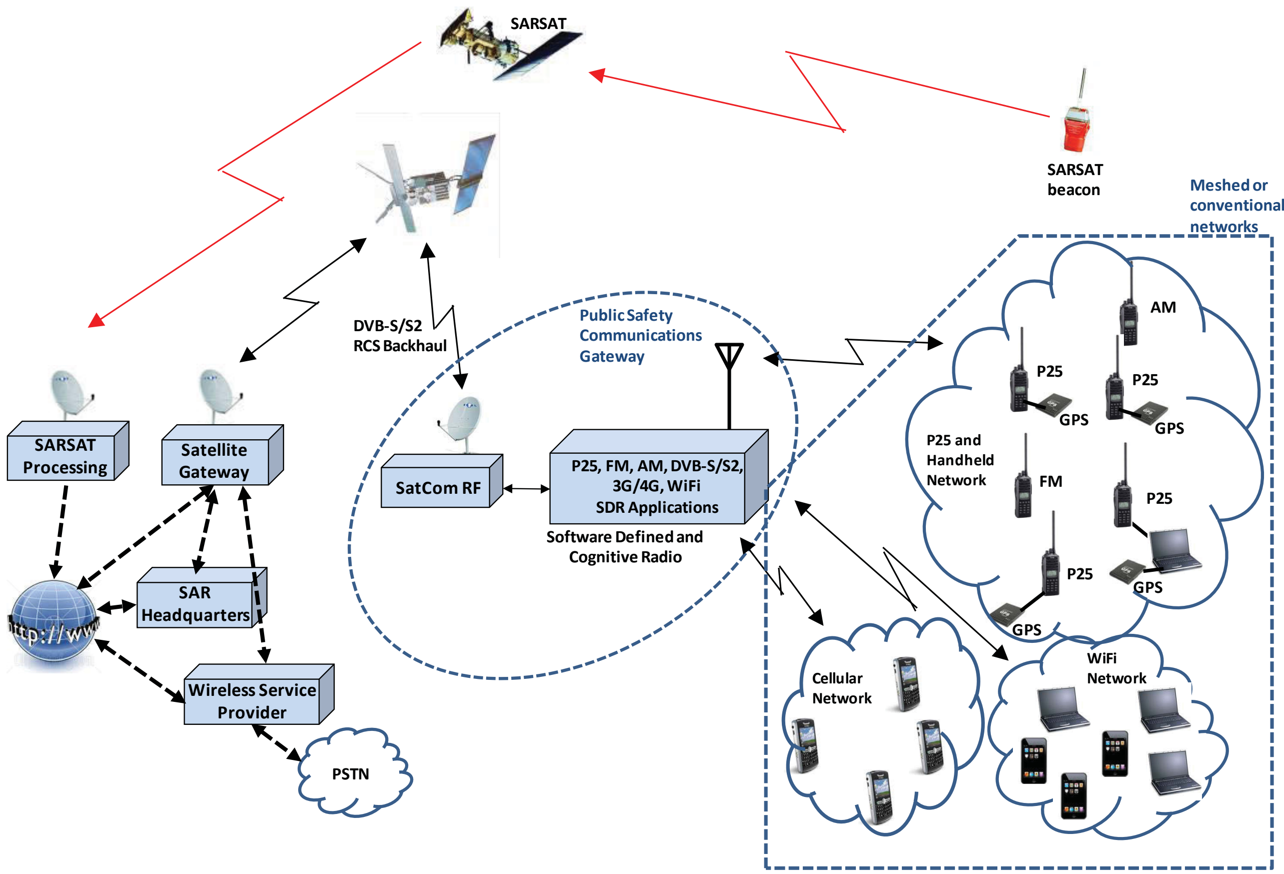

Figure 38: Concept of a Communications Gateway using a satellite backhaul.

CRC's Software Communications Architecture Reference Implementation (SCARI) is used as the SDR framework for the radio implementation [39]. This SCA framework has been augmented with two SCA applications that target specifically the gateway: the Application Controller and the Platform Controller [38]. The former is responsible for loading and unloading applications, such as different access protocols. The Platform Controller is platform specific, and has full knowledge of all the SDR platform resources and is solely responsible for their configuration. It responds to request from the overall radio controller (e.g. for a new waveform), by creating and configuring resources to match the application's requirements, as wells as configuring the affected resources necessary to support it. It also supports the Application Controller in making inter-application connections.

The SDR-based Communications Gateway is currently being developed at CRC, as a proof-of-concept prototype. Bridging between P25 and AM or FM radios has been demonstrated. DVB-S has been implemented on the SDR platform, and work is underway to develop a DVB-S2 waveform. The waveforms have used a combination of FPGAs and General Purpose Processors (GPPs). Graphics Processing Units (GPUs) are currently being investigated, to implement some components of the DVB-S2 waveform.

9.0 Capability Roadmap and Recommendations

In this report, a number of technical options have been presented to extend the coverage of the Public Safety communications network along the Canada-US border. Both existing and emerging technologies have been described. Based on these, this section provides a recommended roadmap for the deployment of infrastructures that could serve to eliminate, or at minimum, reduce the recognized coverage gaps along the border. Recommendations for additional research and development are also made.

It must first be recognized that a single global solution for the complete border does not exist, as each uncovered area has its own uniquec characteristics that will need to be analyzed in much greater detail before any definite solution can be chosen.

Five major criteria were retained in the analysis of recommendations:

- Deployment time
  This would include the time required to procure the equipment, but also to obtain the proper authorizations for deployment and usage. While the purchase of handheld radios can be done rather quickly, it is much longer to obtain the various permits and agreements to deploy antenna towers or to operate in new frequency bands.

- Expected performance
  The performance measure is a combination of data throughput, latency, coverage, availability and interoperability with other systems and organizations. Depending on the expected usage, the performance of the selected system can be tailored to minimize cost. For example, there might be little benefit to deploy permanent broadband infrastructures in low-density remote areas. Temporary and rapidly deployed infrastructures might be a better solution.

- Long term expansion and scalability
  The potential for expansion as demand increases, both in terms of data throughput and additional features.

- Cost
  Cost includes the equipment acquisition, the deployment and the operating costs. It must be analyzed with respect to the usage and expected performance.

- Usage
  Depending on the usage requirement, some solutions may be more appropriate than others. In this case, two main usage types are identified:
  - Routine
    These include daily operations in remote areas such as car accidents and roadside incidents. For these, deployment time and cost have been identified as the major criteria.
  - Exceptional events
    These include special events, such as train derailments, floods, forest fires, and major car accidents. For these, performance and deployment time are identified as the major criteria.

A thorough analysis of each option falls outside the scope of this report but can be further investigated as part of an add-on study.

9.1 Roadmap

Based on the criteria defined above, six options have been selected for consideration to reduce the coverage gap identified in this report.

9.1.1 Partnership with US Organizations

While it is recognized that the coverage analysis presented here does not include all Canadian infrastructures (some were not provided for security reasons), the analysis does show that most of the border is covered by United States Public Safety radio systems. Rather than building a dedicated Canadian infrastructure, a sharing partnership with the US should be considered, if it is indeed verified that gaps in Canadian coverage exist. This would however require some harmonization of the frequency bands to ensure interoperability

As the US infrastructure is already deployed, the Canadian system deployment cost would be minimal.. Negotiating a bilateral collaboration agreement could be challenging, but with the recent push on interoperability and collaboration, the timing for such a negotiation might be right.

Before proceeding however, the performance and scalability of the applicable US systems must be thoroughly analyzed. From insight, it is assumed that the US system is comparable to what is currently deployed on the Canadian side. As such, the US systems would most likely be able to service any of the routine calls, but it is not clear if they could service a major incident.

9.1.2 Partnership with cellular operators

The current report did not analyze the coverage of commercial systems along the Canada-US border. If it were to materialize, such a partnership would most certainly be of benefit to the PS organizations that already make use of such systems in populated areas. Rather than deploying their own systems, Public Safety organizations would benefit from making use of commercial cellular systems. The systems are already deployed and the infrastructure costs are already amortized over thousands of users. Commercial handset radios are inexpensive and carry voice, video and data, often using broadband.

As mentioned earlier, the drawback with such an approach is the system access guarantee (priority access and non-blocking calls), which has not been provided so far by the operators. However, with today's network technology, such guarantees can be offered by establishing an agreed to quality of service (QoS). The main challenge here is for commercial operators to support Public Safety requirements while maintaining a positive business case. An approach that could be considered to address this would be for the Public Safety organizations to own the bandwidth and lease it back to the commercial cellular operators when it is not used by the first responders. As discussed in section 7.4.2, spectrum leasing, using cognitive radio technology, offers an automated approach that maximizes the use of the spectrum, while maintaining the quality of service needed to obtain guaranteed access. If a more rigid quality of service is required, Public Safety could consider a parallel hardware configuration within the commercial operators infrastructure.

Another benefit of partnering with the Telco's is the ability to leverage the rapid evolution of commercial systems. Because of the competition and the number of users, commercial networks tend to evolve much more rapidly than private networks. Public safety systems are still mainly using analog-based systems, and are slowly migrating to a digital environment, while the commercial network is moving to its fourth generation.

The newly announced 700MHz band might be an opportunity to consolidate such a partnership. In this case, the collaboration might not take the form of operating on the same frequencies, but using the same infrastructures for a fully integrated voice and data system.

9.1.3 Satellite communications phones

It is unlikely that commercial systems will cover the complete border. In certain areas, it will simply not be economical to deploy infrastructures (e.g. Yukon – Alaska border). In those cases, satellite communications should be considered. Such phones, provided a direct line of sight with the satellites can be obtained, will provide the connectivity required without any additional costly infrastructure. The usage cost is comparable to regular terrestrial cellular systems. The newer satellite systems being deployed will provide broadband connectivity over handheld devices, and their usage cost should be comparable to regular terrestrial cellular systems. For increased performance, small suitcase terminals can be used and mounted on vehicle roof tops.

Pending a coverage study, such current or future satellite phone services could handle both routine calls as well as those needed in a major incident. In the latter case, poor routine connectivity could be supplemented with suitcase terminals, or by unmanned aerial vehicles, as mentioned in section 6.2.4.

9.1.4 Public Safety infrastructure upgrade

The opening of the 700 MHz band to PS applications will be an opportunity to review the complete communications infrastructure and to define an initial operation capability network model. A detailed coverage analysis should be conducted to maximize the coverage area and to determine antenna sites. In doing so, attempts should be made to make use of existing Public Safety towers and infrastructure. .

The expected deployment time is within a medium term horizon, and provides high potential for performance, expansion and scalability. Its usage could be routine, and could also cover exceptional events so long as the infrastructure has not been damaged.

As suggested above, partnership with commercial operators should be considered to minimize the deployment cost. Leasing the tower might be much cheaper than building their own infrastructure. The Public Safety only infrastructures should be limited to those areas where partnership arrangements with commercial, private, or other public services could not be made (see section 6.3).

9.1.5 Unmanned Aerial Vehicles, airships and high altitude platforms

This option includes a variety of communication range extension solutions including remotely piloted UAVs, airships such as tethered aerostats, and high altitude platforms such as free floating balloons. Such infrastructures can be used to quickly increase the coverage area and provide broadband connectivity to the backbone system.

Smaller size balloons can be rapidly deployed, as they can be stored in the vehicle trunk. Tethered variants of balloons can be recovered more easily after operations, making them an inexpensive solution. Airships, because of their much higher cost and required flying authorizations, could be reserved for the most significant incidents, such as major accidents, floods or forest fires. A small number of those aircraft could be purchased at the national level and deployed when needed.

The technology of tethered and free floating balloons, as well as that of small remotely piloted aircrafts, is well advanced. The technology of the telecommunications payloads to be transported by such relays is also mostly available. Trials would be required to assess these solutions, but they could be added to the Public Safety arsenal within a relatively short timeframe.

9.1.6 Software Defined Radios and Cognitive Radios

In instances where the above mentioned radios do not, by themselves, increase the radio coverage, they can nevertheless form the foundation of a system of systems where ground level communication coverage is augmented by secondary wireless technologies. Software Defined and Cognitive radios will adapt to their environment and select the most appropriate communications channel for the application.

While most radios today claim to be SDR, most of them use proprietary protocols, thereby limiting the potential for scalability. Open architecture and open communications standards should be preferred in order to benefit from the immense leveraging potential.

As cognitive network technologies become more mature, its usage could cover exceptional events where extended coverage will be required to sustain operations.

Additional research and development should be undertaken to further develop the potential of cognitive network topologies.

9.2 Applicability to the Interoperability Continuum

While it was not the purpose of this report to address interoperability issues, the various selected options have nevertheless been mapped on the Interoperability Continuum chart published by the US Department of Homeland Security [40]. As seen in Figure 39, each option offers interoperability potential through various means. UAVs and REMSAT-type of approaches can be seen as gateways, whereby the radio link is split among two or more sections, each having its specific protocol and frequency optimized for that section (e.g. could be WiFi in close proximity, augmented by a UAV link for reach back, and P25 protocol to the final destination). The partnership options with the US PS organizations, Telco's or other private systems could be used for interoperability, but at the expense of converting to proprietary protocols. These options would be the least likely to offer interoperability as the systems are closed. Going to the next step, one could optimize interoperability by selecting open standard systems. The partnership just mentioned could be interoperable in these cases (e.g. standardizing on LTE protocol at 700MHz). The use of SDR/CR technologies could automatically offer communication interoperability by proper upload of the communications protocol.

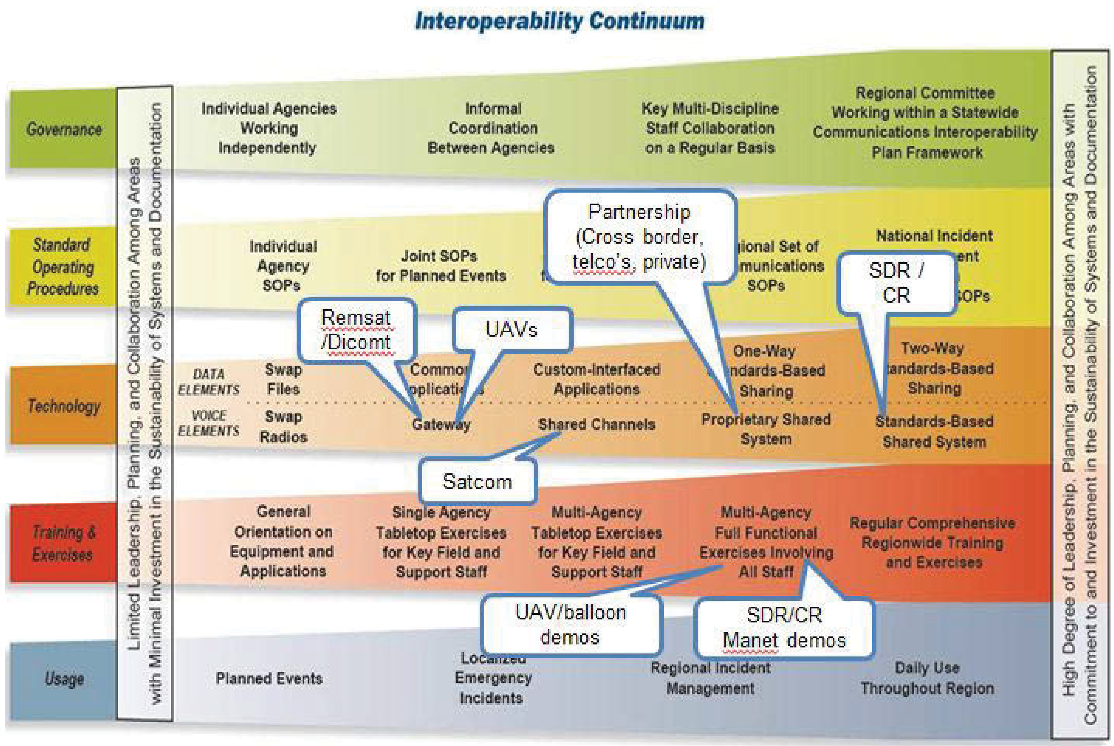

Figure 39 Roadmap options mapped on Interoperability Continuum

9.3 Public Safety Communications Technology Assessment Laboratory

This report has identified a number of potential options to be considered by Public Safety organizations in their attempt to minimize the coverage gap along the Canada-US border. While some are simple extensions of current practices (additional towers), or making use of turnkey commercial systems (cellular network, satellite systems), others require the addition and integration of various technologies into the Public Safety network.

Before moving to acquisition and full deployment, a number of tests and trials should be done to further evaluate the benefit and long term potential of each such option. A Public Safety Technology Assessment Laboratory should be created to perform such tests and trials. It is not the purpose of this report to elaborate on the definition and duties of this lab, but a sample of R&D topics is presented here to show the type of work that could be undertaken. Four topics are presented here, covering short, medium and long term potential R&D programs.

9.3.1 Broadband Wireless Evaluation Network

The communication requirements for Public Safety applications are significantly different than those of commercial networks. For example, PS users are currently more video intensive than users on commercial networks, and as such, specific investigative studies on the performance of PS communication fabrics should be conducted. CRC recommends that in its initial phase, such a staging platform should be designed and implemented at their facilities in Ottawa's West End. A three cell network would be established and used to test a variety of technologies geared to Public Safety such as Long Term Evolution (LTE), range extension technologies, high capacity backhaul, mobile wireless convergence and PS application development to name a few. Performance parameters that would be looked at include network capacity, latency, scalability, ubiquitous mobility and connectivity, and application support.

9.3.2 Unmanned Aerial Vehicle

The feasibility of using UAVs to support broadband range extension communications should be undertaken. Such tests would require the integration of communications devices to a UAV, and trials in various take-off and landing terrains. The UAV's communications payloads could be interchanged, or multiple, to test various communications protocols and scenarios in a gateway configuration with backhaul capability.

This activity could be done in a relatively short time, as most of the technology does exist. It is more a matter of integration and operational testing with first responders in the loop.. The UAV's could be replaced with tethered balloons and or free floating balloon systems.

9.3.3 System interoperability via Software Defined Radio

Because there are many factors influencing the radio coverage map, the number of potential options available is also quite large. This will, without doubt, cause interoperability issues, since the system chosen to address a specific problem will most likely not be optimal in another context. Performance can be optimized with multiple systems, but at the expense of interoperability and higher cost. For large deployments, the concept of gateways, which converts the radio parameters of the users to different radio parameters adapted to the specificity of the link, has been suggested in this report. There are a few commercial systems offering such gateways, but most propose proprietary solutions. A software defined implementation of such a gateway should be completed to evaluate the implementation issues of such an approach, in terms of signal processing, software control and wideband RF front end.

The results of this activity would be available in a medium-term horizon (2-3 years). The development, in software, of the various protocols will take some time. A program has been undertaken at CRC, to investigate the use of SDR technologies in the development of a scalable gateway that could adapt the radio link to best fit the wireless access requirements of public safety operations. AM, FM, P25 and DVB-S protocols have been completed. More work is being performed on the implementation of the DVB-S2 protocol, on the system design of such a gateway.

9.3.4 Cognitive Radio MANET

Mobile ad-hoc networks (MANETs) offer the potential to create networks and reach back capabilities with minimum permanent infrastructure. The communication finds its way to destination by selecting the best open path available. CR-MANETs could create a paradigm shift in the PS communications network infrastructure, especially when combined with cognitive radio technology, which is seen by many as the ultimate radio type since it can adapt itself automatically to the environment to make best use of the various surrounding communications systems. A CR-MANET would consist of a set of cognitive radios that collaborate in deciding what band is the most suitable based on signal propagating environment and system parameters, and then configure the wireless network appropriately. Based on the IP protocol, the CR, which would be implemented with SDR technologies, would find collaborative radios, adapt its operating parameters and select the best communications path to destination. The UAV's equipped with SDR could also be an integral part of the CR-MANETs and offer Beyond-line-of-Sight situation awareness to the PS personnel.

This research activity is a much longer term activity.

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