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DYNAMIC SPECTRUM ACCESS (DSA) ENABLED COGNITIVE RADIOS FOR FIRST RESPONDERS' CRITICAL NETWORKS

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DSA enabled Cognitive Radio Networking for First Responders' Critical Networks

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I. Introduction

Disasters such as the Hurricane katrina [1], $9/11$ attack on the world trade center [2], Minnesota bridge collapse [3] or the collapse of terminal 2E at Paris Charles de Gaule Airport [4] often focus on the importance of (wireless) communication and interoperable, ubiquitous connectivity for First responders (e.g., police, military, fire-fighters, medical). The wireless communication industry is recently going through major advancements and innovations. With the transformation from second generation (2G) wireless cellular technology to third and fourth generation (3G and 4G) technologies, the scope of wireless networking is increasing almost exponentially in the recent time and so is the demand for radio spectrum in wireless networking from commercial service providers, first responders and military tactical networks.

In most countries, the competitive behavior among wireless service providers for spectrum was initiated by spectrum auctions held in 2000 and 2001. Though the auctions were very successful in some countries (e.g., United Kingdom, Germany), they were open to criticism in others (e.g., Austria, Switzerland, Netherlands) [5]. Through FCC, the spectrum was auctioned in the United States – the results of which are hotly debated. Moreover, FCC sets the rules and regulation which govern the access to spectrum. These rules have led to allocation of spectrum chunks for specific purposes; e.g., 824–849 MHz, 1.85–1.91 GHz, 1.930–1.99 GHz frequency bands are reserved for licensed cellular and PCS services and require a valid FCC license, whereas 902–928 MHz, 2.40–2.50 GHz, 5.725–5.825 GHz frequency ranges are reserved as free–for–all unlicensed bands [6].

A. Disadvantages due to Static Spectrum Allocation

This kind of static allocation of spectrum has several disadvantages because of being time and space invariant. In static spectrum allocation, parts of the radio spectrum have been statically allocated for various wireless networking services for the military, government, commercial, private and public safety systems. These spectrum allocations are usually long-term and any changes are made under the strict guidance of a governmental agency. In the United States, there are two regulatory bodies that regulate and manage the use of radio spectrum. Federal Communications Commission (FCC) regulates spectrum for non-governmental use. The National Telecommunications and Information Administration (http://www.ntia.doc.gov/) regulates spectrum use for federal government users including the Department of Defense (DoD). It is worth noting that the spectrum usage pattern for first responders/military and commercial systems are quite different. While commercial services apparently show a somewhat steady use (on a day to day time scale), public safety spectrum is in great demand (due to high volume communications) during times of disaster/emergency. Arguably on the other hand, spectrum is under-utilized in a "normal" scenario. Though, this low usage of spectrum has forced the DoD to relinquish parts of its spectrum, the fact remains that both military and first responders have a growing need for spectrum-dependent operations to ensure safety in an ever-changing global community and there is already a contention for acquiring spectrum rights [7] among public safety and commercial wireless service providers.

One may argue that spectrum allocated to cellular and PCS network operators are highly utilized. But in reality, spectrum utilization even in these companies vary over time and space and undergo under-utilization. One typical example could be Super bowl competition. While at the time and space of Super bowl, there is an excessive demand for spectrum for wireless services, other times it may simply be under-utilized. Often times, the usage of spectrum in certain networks is lower than anticipated, while there might be a crisis in others if the demands of the users using that network exceed the network capacity. Static allocation of spectrum fails to address these issues of spectrum sharing even if the service providers (with statically allocated spectrum) are willing to pay for extra amount of spectrum for a short period of time if there is a demand from the users it supports.

Static spectrum allocation additionally faces difficulties due to the modification of old technologies. For example, in case of VHF and UHF bands reserved for television broadcast in the United States, allocation of 6 MHz per TV channel was based on old analog NTSC system even though better quality video can be now broadcasted with almost 50% less spectrum per channel [8]. Given the pervasive penetration of

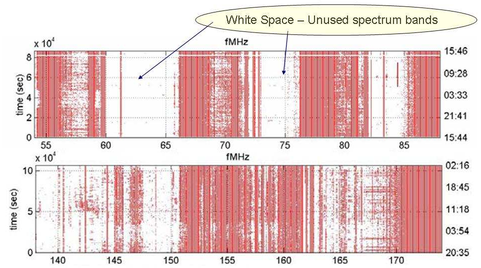

Fig. 1. Example of “White space” in spectrum usage (Courtesy: Shared Spectrum Company)

cable–TV, this precious spectrum, though allocated and owned, remains unused in most locations. This has recently triggered the famous digital TV transition [9] by FCC to open up spectrum for commercial and public safety usage.

Another major problem with the static spectrum allocation and the legacy static radio technology is the lack of interoperability between different organizations of first responders. There have been examples of failure in communication between different organizations at World Trade Center on $9/11$ [10] and other disaster areas due to lack of interoperability in the legacy radios.

II. THE FUTURE PARADIGM OF DYNAMIC SPECTRUM ACCESS (DSA)

It has been well–established that there is a great amount of unused bands available sparsely which could be exploited by both licensed and unlicensed services. Thus uncoordinated, opportunistic deployment of spectrum chunks has led to an “artificial scarcity of spectrum”. An experimental study conducted by Shared Spectrum Company during the 2004 Republic National Convention [11] found that spectrum utilization is typically time and space dependent and there is a great amount of “white space” (unused bands) as shown in figure 1. As a result, it is intuitive that static spectrum allocation may not be the optimal solution toward efficient spectrum access for both licensed and unlicensed services. With the dis–proportionate and time–varying demand and hence usage of the spectrum, the notion of fixed spectrum assignment to providers is questionable. Though it might be argued that the implementation and administration is very easy, the fact remains that the current system is ineffective and deprives service providers, end–users, and FCC from maximizing their benefits.

A. Dynamic Spectrum Access and Cognitive Radio

In order to break away from the inflexibility and inefficiencies of static allocation, a new concept of *Dynamic Spectrum Access* (DSA) is being investigated by network and radio engineers, policy makers, and economists. In DSA, spectrum will be accessed dynamically depending on need of the service providers which in turn depends on end users' demands in a time and space variant manner. Emerging wireless technologies such as cognitive radios [12] is poised to make DSA a reality. This method of spectrum sharing is more efficient and will help service providers, and regulatory bodies like FCC to avoid any artificial scarcity.

With the new paradigm of cognitive radio technology, it will be possible to operate at any unused frequency channel to maximize the spectrum usage opportunity. The regulatory aspect from FCC in this new DSA policy is that cognitive radios must not interfere with the incumbent radio operation (if any) in a band – who are the prioritized users of that band. To make the DSA mechanism successful cognitive radio systems perform spectrum sensing, dynamically identify unused ("white") spectrum, and operate in this spectrum band when it is not used by the incumbent radio systems – who are the primary users of this band. Upon detecting incumbents in any band cognitive radio must automatically switch to another channel or mode.

B. Differences from existing static radio technology

In existing implemented technology (e.g., WiFI or WiMAX or similar wireless access technologies), static radio devices are dominantly functional. However, static radio devices have the following disadvantages:

- The static radio devices can operate only on a single frequency channel in the entire network at a time. Lack of interoperability due to such constraints is clearly a major issue with the static radio.
- The static radio device can not automatically configure itself to switch to other frequency bands even if there are multiple orthogonal frequencies available in the network.
- In the legacy IEEE 802.11 system, a single wireless card can connect to only one wireless access point (AP) in the infrastructure mode or a single ad hoc network in the ad hoc mode, using only one frequency channel in the entire network even though there are multiple frequency bands available in a IEEE 802.11a/b/g network.
- Simultaneous connections to multiple networks are not possible with the static radio device.

In contrast to the legacy static radio devices, cognitive radios are envisioned as the software-defined "intelligent" radios that would learn from the environment to adopt and would act accordingly. For example, these radios can automatically detect which spectral band is unused and switch a user to this band. They can learn and predict the spectral usage patterns in a geographical area and adapt the medium access control protocol accordingly. They can even learn to adapt to the environment the first responders are in. For example, in urban environment with buildings and obstacles, a cognitive radio would likely to choose a low frequency channel; a low frequency signal can travel farther, penetrate walls and other obstacles better than high frequency channels.

The major benefits that the cognitive radios are envisioned to provide to the first responders networks are:

- Software-driven simultaneous connectivity with infrastructure and ad hoc network by dynamic channel switching.
- Simultaneous connectivity with multiple ad hoc networks: The virtualized wireless card can connect to multiple ad hoc networks by channel switching. These features clearly help in achieving seamless interoperability.
- Efficient spectrum usage: For example, in existing IEEE 802.11 networks the legacy devices in the entire network can only use one channel while most of the other frequency channels are unused or underused. The contention and hence interference for this one channel among different nodes are very high. With the proposed software driven cognitive radios, the frequency resources would be used dynamically and efficiently. With multiple channels being used, contention and interference will be reduced significantly.
- Extended coverage and capacity with multiple channel access.
- Cost and scalability: Even though one may argue that connecting to multiple networks can be done using multiple physically different wireless cards, it comes with some drawbacks: higher battery energy consumption, cost, etc. The proposed cognitive radio paradigm with software driven spectrum access alleviates these drawbacks.

With the above-mentioned benefits, DSA enabled interoperable cognitive radio architecture can create wide-area back-haul networks where traffic can flow among the peers directly or using relay/forwarding resulting in higher capacity, ubiquitous connectivity and increased coverage as shown in Fig. 2.

III. Research challenges

The new DSA policy would allow unused spectrum bands (white spaces) to be used dynamically by unlicensed secondary users under the provision that they would vacate upon the return of the primary user. The success of this policy depends on the ability of secondary users to dynamically identify and access unused spectrum bands, detect the return of primary users and switch to a different band promptly upon sensing the primary user. The newly proposed Cognitive Radio (CR) paradigm/networks are anticipated to make DSA a reality. In contrast to the legacy radios, CRs are envisioned to intelligently adjust their

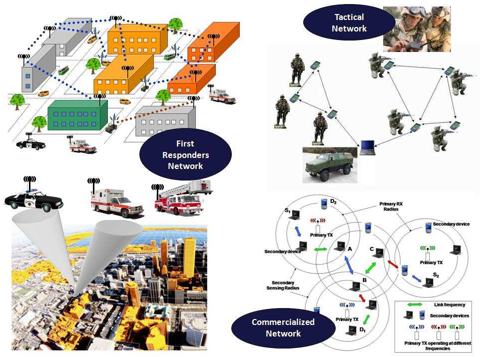

Fig. 2. Various wireless cognitive networks examples

transmission/reception parameters themselves based on learning and interaction with the environment and find the best available spectrum bands to use.

Accordingly, the issues in the design of cognitive radios (CR) and cognitive radio networks (CRN) must be better studied for the concept of interoperability and dynamic spectrum access (DSA) to reach its full potential. Several layers of the traditional network protocol stack will need to be enhanced to accommodate the additional functionalities of cognitive radios.

- Sensing: The physical layer will need to sense for spectrum holes (scanning the spectrum and processing wide-band signals) and continuously adapt its operating power, spectrum band and modulation without human intervention.
- Medium Access: The medium access (MAC) layer must intelligently cooperate with the sensing measurement and coordinate dynamic spectrum access to avoid interference, self-coexist with other devices and avoid primaries.
- Routing: Subsequently, the network layer must be aware of several parameters gathered in the MAC and PHY layers to cooperate with these lower layers and perform spectrum-aware routing.

IV. Vulnerability Challenges

Also, in spite of cognitive radio technologies fast emerging as a next generation wireless networking platform, initial research has hardly focused on security aspects of CRNs from different classes of attacks from malicious nodes/users. The attack may happen in the form of

- Jamming - malicious intention of distorting normal secondary communications
- Denial of Service attack - emulating characteristics of primary users of the spectrum band (malicious intention of evacuating the secondary users from the spectrum band and capturing the band)

- Eavesdropping by emulating characteristics of secondary users.

Thus sensing/detection of the attacks from malicious users is an important task to build efficient and secure DSA system so that these attacks cannot shut down a first responder or similar emergency tactical networks during critical periods. Security against these classes of attacks cannot be achieved through cryptographic means alone. In this research, I plan to explore ideas from behavioral models, game theory, economic models and stochastic learning to optimize decisions under uncertainty and implement new cross layer optimization security protocols for dynamic spectrum access networks.

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