Dynamic Spectrum Management for Military Wireless Networks

Piotr GAJEWSKI
Institute of Telecommunications, Military University of Technology
POLAND

Marek SUCHAŃSKI
Military Communication Institute
POLAND

ABSTRACT

The dynamic spectrum management for military wireless networks is discussed in this paper. Rapidly growing demands for services accessed by wireless networks call to have the efficient tools for spectrum allocation during mission planning and supervision. Two architectures (CJSMPT, DIMSUMNet) for legacy and modernized equipments are described. An opportunistic spectrum access is the most promising method for future cognitive radio networks (CRN). The general concept of cognitive radio (CR) as well as some standardization works concerning cognitive and dynamic spectrum access are described. The IEEE 802.22 standard proposed for CR wireless area networks is shortly characterized. Some challenges concerning OSA policy based concept are discussed.

1.0 INTRODUCTION

A static spectrum utilization has significant operational implications which have been brought to light by expensive spectrum utilization measurements [1]. It showed that a large part of the radio spectrum is allocated but barely used in most locations.

The current spectrum management methods have left very little spectrum to allocate both for new services and for expansion of existed services, leading to an artificial spectrum scarcity, even though large parts of spectrum remains underutilized.

Military missions of the last 20 years appeared as a great experience in the area of simultaneous exploitation of huge number wireless networks in small area. Such situations abounded with collisions of this systems creating serious danger for own combat units. For this reason in US army problem of rationalization of spectrum consumption through using more effective spectrum managements methods is treated as a one of problems demanding urgent solution [2].

Dramatically growth users demands of wireless access to the information and communications services calls for more and more efficient methods for spectrum utility. Frequency spectrum is one of the really natural resources in a global information society.

The term “dynamic spectrum management” (DSM) covers a range of different subjects areas like dynamic channel allocation (DCA), frequency assignment, spectrum coexistence and spectrum access both to the licensed and unlicensed frequency bands. Several implementations of a real-time DSM algorithms have been already studied and recently published [3] ÷ [7] including triggering of DSM algorithm, management of the traffic on the used carriers, adaptation of radiated power, coding and modulation, beam-forming technique, prediction of networks loading, and allocation decisions. Each of above listed questions should be solved by means specialized optimization methods. Figure 1 shows the general classification of modern DSM methods.

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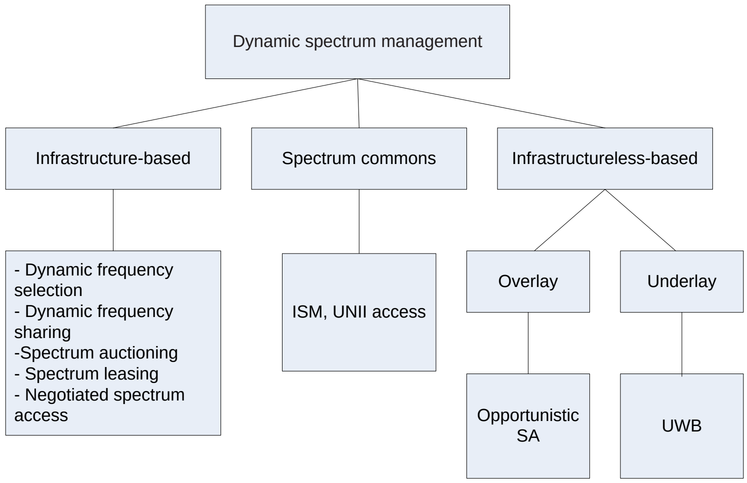

Figure 1: DSM Methods Classification.

The possibility of centralized and distributed DSM is one of the main question to solve for wireless system architecture. Bellow some problems concerning infrastructure-based and infrastructureless-based are discussed both for legacy and new proposed wireless military networks.

Currently exploited software tools dedicated to spectrum management (SPECTRUM XXI, Battlefield Spectrum Management etc.) are developed for less flexible systems of which configuration times were longer and operating tempo was slower [8]. Current combat operations are very dynamic so wireless systems become more flexible, more mobile and are used in increasing operating tempo. This creates demands to develop new philosophy of spectrum utilization – Dynamic Spectrum Access (DSA) and consequently – Dynamic Spectrum Management systems (DSM). Nowadays there are considered two kinds of DSA architecture, namely [9]:

1) Coordinated Dynamic Spectrum Access (CDSA) relies on certain infrastructure including a spectrum broker as a principal component.
2) Opportunistic Spectrum Access (OSA) which is embodiment of the concept of opportunistic using of unoccupied spectrum ("spectrum holes") with basic tenet "Cause – No – Harm". In this philosophy spectrum broker doesn't exist.

Figure 2 adapted from [10], depicts the overall spectrum access taxonomy – from the current regime of static spectrum access, with the least flexible spectrum use, to the most flexible spectrum use enabled by OSA.

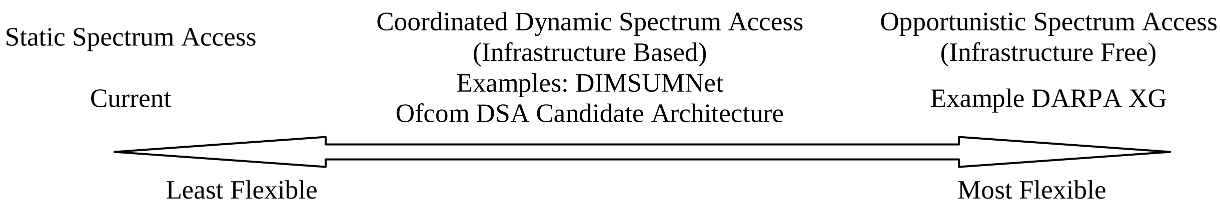

Figure 2: Spectrum Access Taxonomy.

In the range of options for DSA depicted in Fig. 2 from the current static spectrum allocation and assignment on one end to the most challenging OSA at the other end, Coordinated DSA is located between this two architectures. The crux, and also common feature of CDSA is the use of a spectrum broker for coordinating spectrum access.

In the most challenging OSA architecture – for which an embodiment will be new generation of radio systems called “Cognitive Radio” (CR) – basic principle of acting can be called “Cause – No – Harm”. In this case secondary users, sharing spectrum, perform opportunistically seeking out unoccupied spectrum (“Spectrum Holes”) and, at the same time, avoiding interference to primary users. A CR with spectrum-sensing capability, and cooperative opportunistic frequency selection, is an enabling technology for faster deployment and increased spatial reuse.

The new term “spectrum society” arises during last decade. The increasing in computational abilities, artificial intelligence and especially in optimizing algorithm for wireless networks adaptation have to start thinking about cognitive functionalities of networks and devices. Growing interest in CR is demonstrated by start of the IEEE Communications Society Technical Committee on Cognitive Networks [11] as well as increasing interest for IEEE DySPAN (Dynamic Spectrum Access Network) annual symposia. Since 1999, as main activities can be enumerated: 2002 (United States) DARPA initiates the XG (NeXt Generation) project to investigate the potential for the military to share spectrum spatially and temporally with multiple devices, 2003 (European Union) Information Society Technologies include dynamic spectrum access technologies as part of the Sixth Framework Program of R&D, 2004 (European Union): End-to-End Reconfigurability (E2ER) Project initiated in Information Society Technologies, 2005 (United States): DARPA XG and NSF projects complete a series of spectrum occupancy measurements indicating less than 10 percent occupancy in time–space under 3 GHz, 2008 (United States): DARPA XG successfully demonstrates Opportunistic Spectrum Access. Also in EU 7th Framework Program some questions concerning DSA have to be solved.

2.0 COORDINATED DYNAMIC MANAGEMENT SYSTEM

As was mentioned earlier the crux and also common future of CDSA is the use of a spectrum broker for coordinating spectrum access.

Wide variety possible implementation of this philosophy is bounded by two concepts, as follows:

- Applicable for legacy systems – represented by The Coalition Joint Spectrum Management Planning Tool (CJSMPT) described in [8],
- Applicable for upgraded (modernized) systems – represented by Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile – access Networks (DIMSUMNet) described in [12].

CJSMPT is a tool developed for U.S. ARMY CERDEC (Communication – Electronics Research, Development and Engineering Center). CJSMPT architecture shown in Fig. 3 comprises of five key components that coordinate to perform the spectrum management planning and RF deconfliction processes:

- Spectrum Manager (SM) coordinates overall operation of the system and executes de-confliction algorithms;
- Communication Effects Simulator (CES) simulates anticipated missions to predict conflicts;
- Visualisor (VIZ) visualizes spectrum use including electronic warfare (EW) effects;
- Spectrum Knowledge Repository (SKR) contains key scenario data to support simulation of mission (force structure, emitter characteristics, spectrum usage, etc.);
- Framework provides open service oriented architecture with mechanisms for component date exchange.

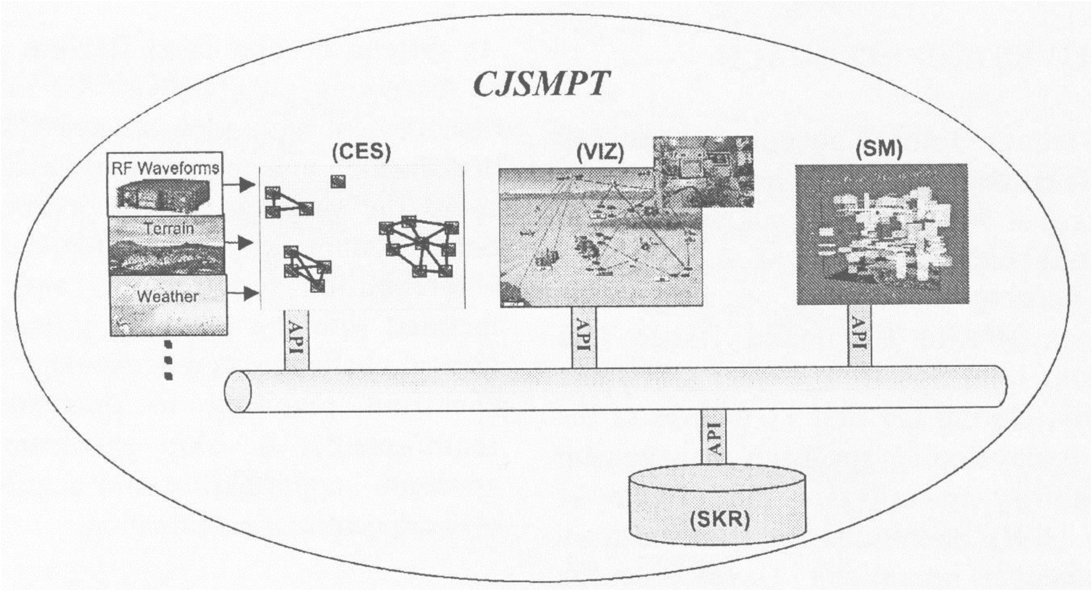

Figure 3: CJSMP Architecture.

The heart of the CJSMPT is Spectrum Plan Advisor (SPA), element of the SM performing de-confliction and optimization based on interference report output by CES, accounting for anticipated movement (including EW missions) and propagation effects.

This system can be treated as upgraded legacy planning tool involving movement of wireless networks, EW effects, etc., working in near-real time(tests showed that it generates a conflict-free spectrum plan in less than 30 sec for 50 nodes).

DIMSUMNet is the implementation of idea of CDSA introduced in [12] for infrastructure based multi-provider cellular, fixed-wireless access and mesh networks. In this concept service providers and users of this networks do not apriori own any spectrum; instead they obtain time bound rights from a regional spectrum broker to a part of the spectrum and configure it to offer the network service. Realization of this model requires new technologies in the form of coordination, signaling protocols, network elements and client devices.

To reach practical realisability the concept of Coordinated Access Band (CAB) was introduced. Illustrated in Fig. 4, CAB is contiguous chunk of spectrum reserved by regulatory authorities for controlled dynamic access.

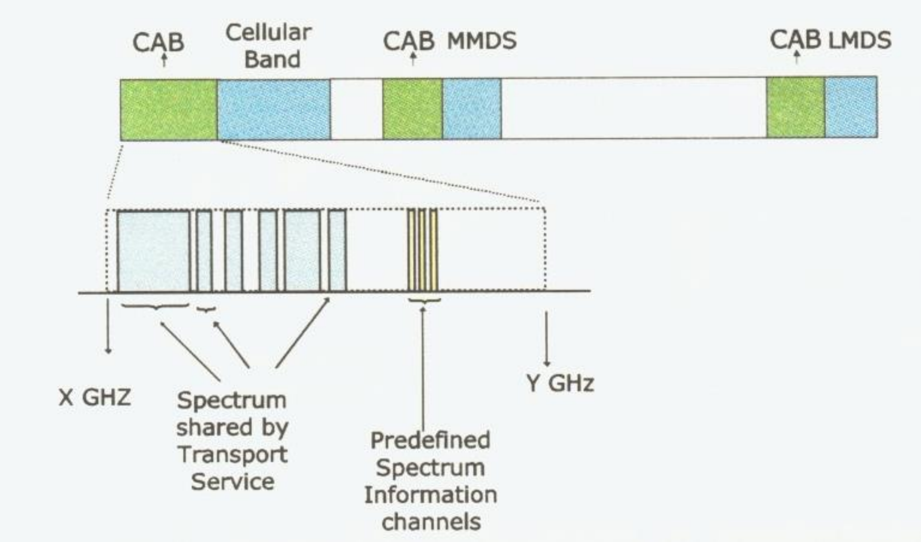

Figure 4: Coordinated Access Band (CAB).

For geographical region, location of various parts of CAB spectrum to individual networks or users is controlled by a spectrum broker. As such, the spectrum broker permanently owns the CAB spectrum and only grants at time bound lease to the requestors. The lease conditions may specify addition parameters such as the extend of special region for spectrum use, maximum power and exclusive or non-exclusive nature of the lease. The compliant use of CAB spectrum requires that the “lessee” entity return the spectrum to the broker at the end of the lease. The CAB band resembles a licensed band in that the spectrum lease is a short-duration license. CAB leases are awarded by an automated machine-driven protocol. The authors of this concept consider two models for CAB usage. In this simplest model (CAB-M1), requests for CAB spectrum can be generated only by the network operators. In the more complex model (CAB-M2), the end user Mobile Node (MN) devices (PDAs, laptops, PCs) participate in the spectrum leasing process and request spectrum for communication with peer enduser devices or with network elements such a base stations.

Within a simple CAB, certain fixed frequencies are reserved as a Spectrum Information (SPI) channels.

Based on this concept authors have proposed architecture of system realizing their brokering idea as a Dynamic Intelligent Management of Spectrum for Ubiquitous Mobile-access Network (DIMSUMNet), shown on Fig. 5.

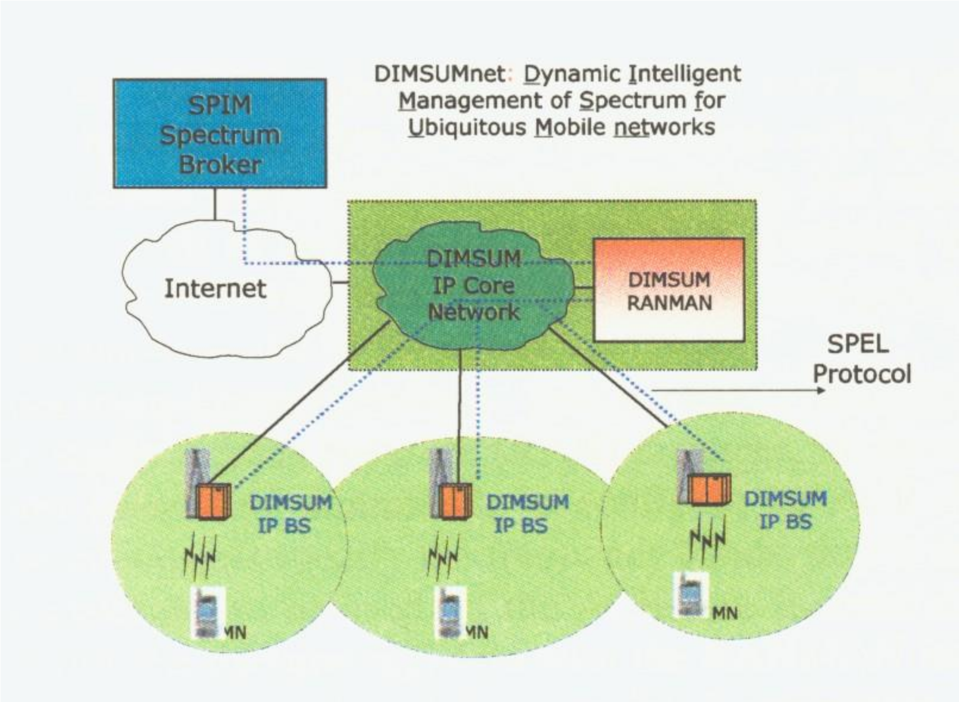

Figure 5: DIMSUMNet Architecture.

The main components of the DIMSUMNet are:

- SPectrum Information and Management broker (SPIM),
- Radio Access Network (RAN) consisting of new type of base stations,
- RAN MANager (RANMAN),
- New intelligent enduser devices.

3.0 OPPORTUNISTIC SPECTRUM MANAGEMENT

An opportunistic spectrum management is the most promising technology for dynamical spectrum access that has a potential to mitigate spectrum scarcity and meet the increasing demand for spectrum utility. A CR technology has the potential of being a disruptive force within spectrum management. This section establishes the process and anticipates performance of dynamic spectrum access within CR systems. This is important for three reasons:

1) The DSA mechanism is an inherent element in any adaptive wireless structure. The DSA-enabled techniques include front-end linearity management, dynamic topology, and waveform selection. Even if the spectrum management benefits were nonexistent, the flexibility it affords to manage other aspects of the wireless environment justifies its inclusion.

2) DSA offers capability benefits through pooling of spectrum resources and managing spectrum conflict resolution dynamically.

3) DSA radios are inherently interference tolerant, and therefore radios sharing spectrum with CRs can be more aggressive in their spectrum reuse policies since, if they occasionally cause interference, the interference can be resolved directly by the CR.

A key measure of a DSA system is its ability to provide more spectrum access in order to create a corresponding increase in network capability. In examining the operation of DSA performance, three cases could be considered:

1) A manually de-conflicted spectrum that is statically assigned without specific (realtime) knowledge of user location, actual usage, or bandwidth needs.
2) Cognitive radios that share spectrum with, and avoid, interference with noncooperative systems.
3) Cognitive radios sharing spectrum with other CRs, minimizing, but not necessarily avoiding, interference with other users, on the assumption that they can resolve interference autonomously.

The cognitive radio terminology was firstly introduced by Joseph Mitola III and widely described in his dissertation [13]. The SDR Forum and the IEEE recently approved the following definition of a cognitive radio:[1]

a) Radio in which communications systems are aware of their environment and internal state, and can make decisions about their radio operating behavior based on that information and predefined objectives. The environmental information may or may not include location information related to communication systems.
b) Cognitive radio (as defined in a) that uses SDR, adaptive radio, and other technologies to automatically adapt to the radio environment.

Fig. 6 shows the functional scheme of CR.

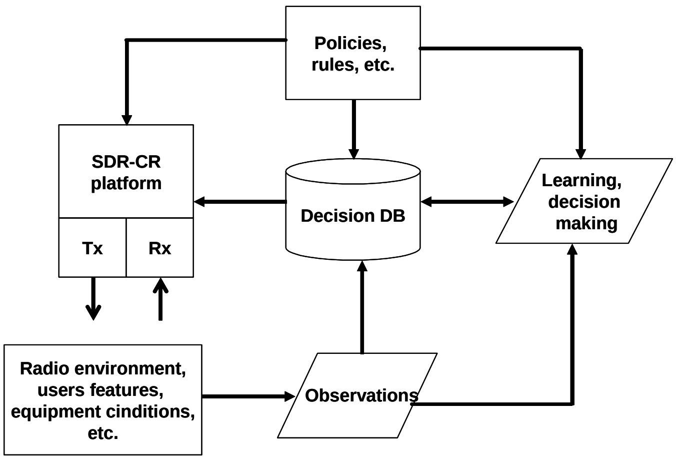

Figure 6: The General Scheme of Cognitive Radio.

CR should support the following basic functionalities:

- Radio platform (SDR – SCA – Software Communications Architecture - based)
- Environment recognition and evaluation
- Environment and CR parameters and behavior description (observations and data base DB).

Some CR architectures and functionalities as well as DSM in CR networks have been widely studied and described e.g. [14], [15], [16]. Generally CRs consist of four basic capabilities: flexibility – to change waveform and configuration; agility – to change the spectral band in which to operate; sensing – to

[1] See http://www.sdrforum.org/pages/documentLibrary/documents/SDRF-06-R-0011-V1_0_0.pdf.

observe the state of the system; and networking – to communicate between multiple nodes with relatively big network capacity.

The ability of a device to be aware of its environment and to adapt to enhance its performance, and the performance of the network, allows a transition from a manual, oversight process to an automated, device-oriented process. This ability has the potential to allow a much more intensive use of the spectrum by lowering the spectrum access barrier to entry for new devices and services as well as to radically change the spectrum management policies for spectrum policymaker and policy regulator.

The spectrum management framework for CR network is illustrated in Fig. 7 [17]. It is typical example of cross-layer design approach.

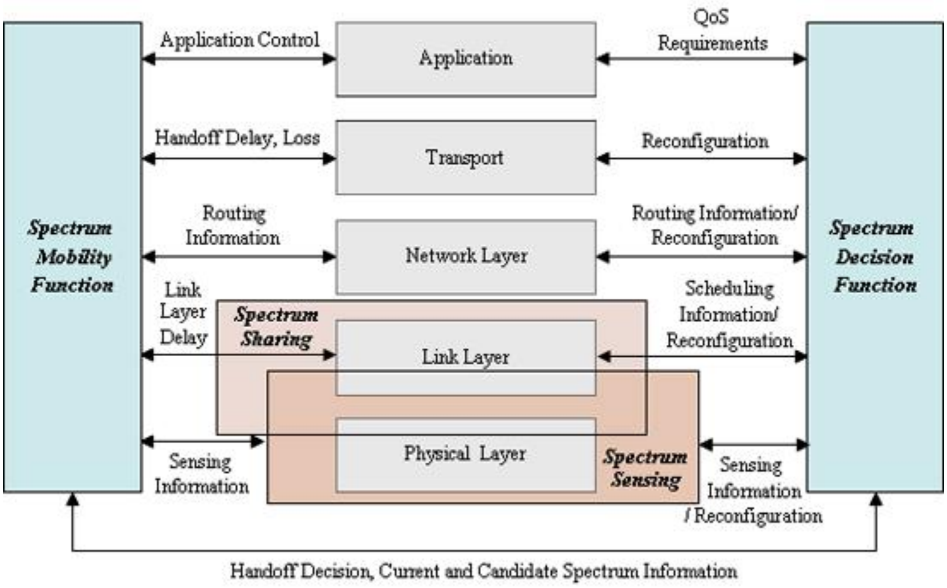

Figure 7: The SM Framework for CR [17].

The spectrum management process consists of four major steps:

- Spectrum Sensing: A CR user can only allocate an unused portion of the spectrum. Therefore, the CR user should monitor the available spectrum bands, capture their information, and then detect the spectrum holes.
- Spectrum Decision: Based on the spectrum availability, CR users can allocate a channel. This allocation not only depends on spectrum availability, but it is also determined based on internal (and possibly external) policies.
- Spectrum Sharing: Since there may be multiple CR users trying to access the spectrum, CR network access should be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.
- Spectrum Mobility: users are regarded as “visitors” to the spectrum. Hence, if the specific portion of the spectrum in use is required by a primary user, the communication needs to be continued in another vacant portion of the spectrum.

One of the most common capabilities of a CR is the ability to intelligently utilize available spectrum based on awareness of actual activity. The cognitive radio can adapt for the spectrum regulator, the network operator, and the user objectives. The CR may also exhibit behaviors that are more directly apparent to the user like awareness of geographic location, awareness of local networks and their available services, awareness of the user and the user's biometric authentication to validate various transactions, and awareness of the user and his or her prioritized objectives.

The CR spectrum access model (Fig. 8) enables policies, users, sensors, and protocols [18] that should be determined and solved for whole OSA environment. The general spectrum access regime is presented in Fig. 9 [18].

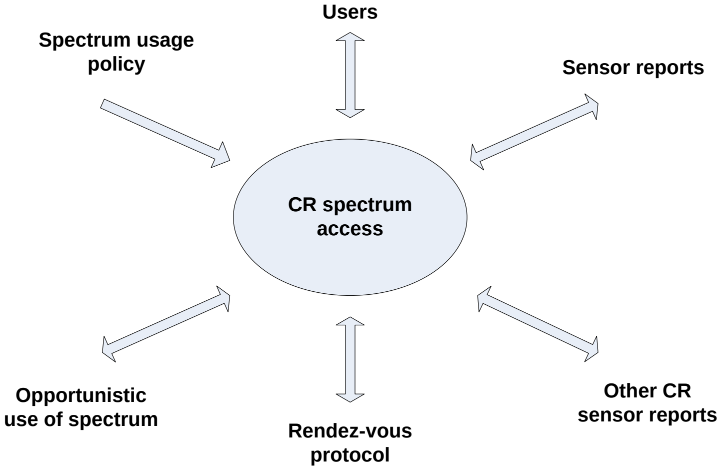

Figure 8: CR Spectrum Access Model.

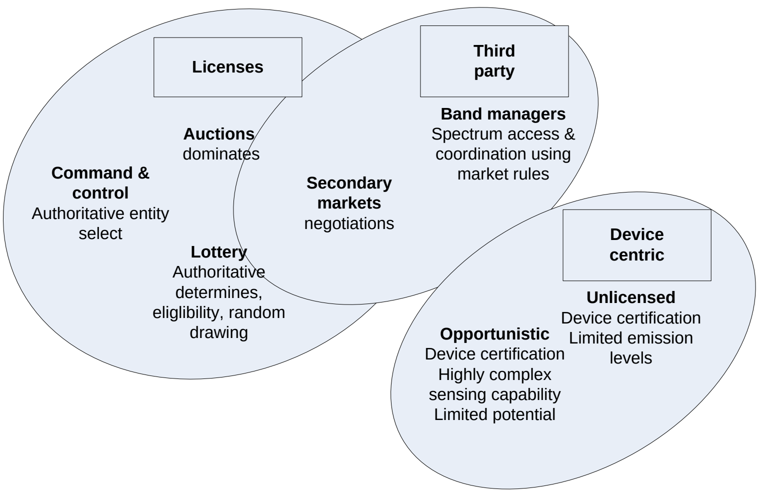

Figure 9: Spectrum Access Regime.

As we can see from Fig. 9, the OSA methods should taken into account licensed users (primary users) and operators, third party users (secondary users), as well as possibilities of used devices. So, the best solution will come from so called policy based radio. It is a radio that is controlled by a predetermined set of rules for behavior. These rules can be defined and implemented during manufacture or during configuration of a device by the user, or during over-the-air provisioning and/or by over-the-air control.

The OSA flexibility is dependent on many factors concerning each layer of system protocol stack (Fig. 7). The special cases of OSA flexibility features are reflected in Fig. 10 [18].

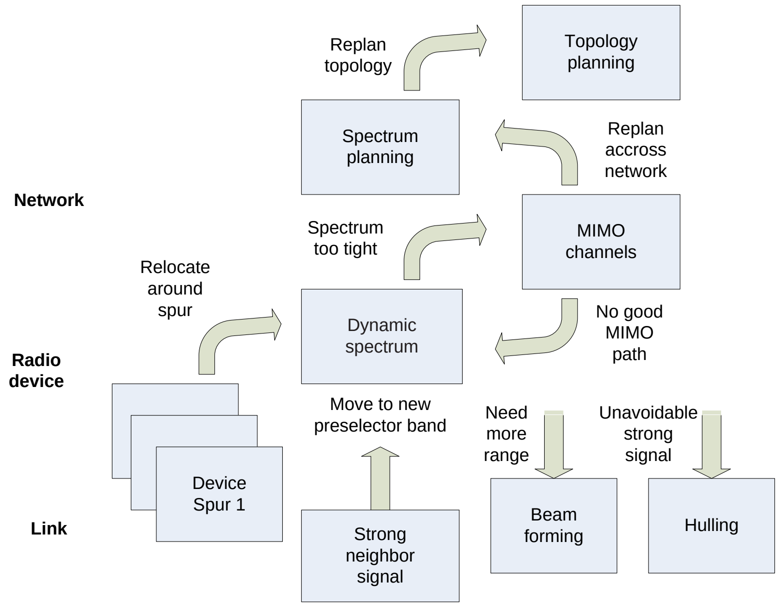

Figure 10: The OSA Flexibility.

Time, space, and interference are three operational dimensions for available spectrum policies. One example for time policy are transactions within the secondary market for licensed spectrum use. Another one could be a noncooperative use of spectrum that is currently not in use. Space policy is depicted in cases where the location of a device could determine its operational characteristics. One proposal for spatial dynamics includes the allowance of higher-power transmission of unlicensed devices in rural environment. Another proposal is the use of unlicensed devices in bands where the device is sufficiently far away from a transmitter. Interference dynamics would need to understand not only its environment but also the impact of its own transmission on the surrounding environment. The capacity to accurately measure and model the environment would be needed.

Currently, three basic types of assignment methods are generally employed: command and control, auctions, and protocols and etiquettes. Command and control assignments are provided by the regulatory agency by reviewing specific licensing applications and choosing the prospective licensee by criteria specific to the national goals. This directly challenged their authority in using spectrum for the benefit of the country (i.e., its citizens). Auctions are now a common form for spectrum assignments throughout the industrial world. Unlicensed devices and amateur licensees do not have specific frequency assignments. The Protocols and Etiquettes methods allow these devices to operate within a band, and the selection of a particular frequency. Protocols are explicit interactions for spectrum access like e.g. Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) a protocol. Etiquettes are rules that are followed without explicit interaction between devices. Simple etiquettes, such as “listen before talk,” dynamic frequency selection (DFS), and power density limits are one-sided processes.

The policy-based OSA system consists four parts [18] that defined policy decisions, policy services, policy enforcements, and status monitor (Fig. 11).

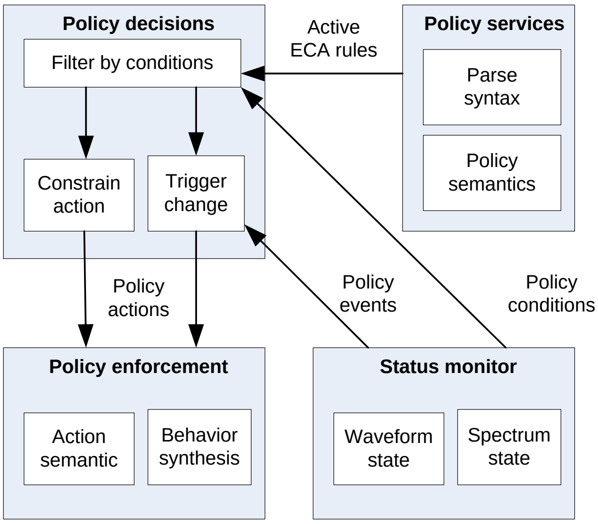

Figure 11: Policy-Based OSA Model.

Currently, many research works concern the PHY and MAC procedures for opportunistic spectrum access of secondary users using modern adaptation technologies like power control, channels allocation, access control [4], modulation and coding adaptation etc. with various techniques of optimization e.g. game theory, neuronal networks, graph coloring, tabu search etc. Some of proposed methods use the channel state information (CSI) coming from the feedback channel measurements or distributed by network nodes.

Policy-based model can be implemented and deployed for military proposes as hierarchical structure enabling network operational center and some number of cooperative tactical centers (Fig. 12).

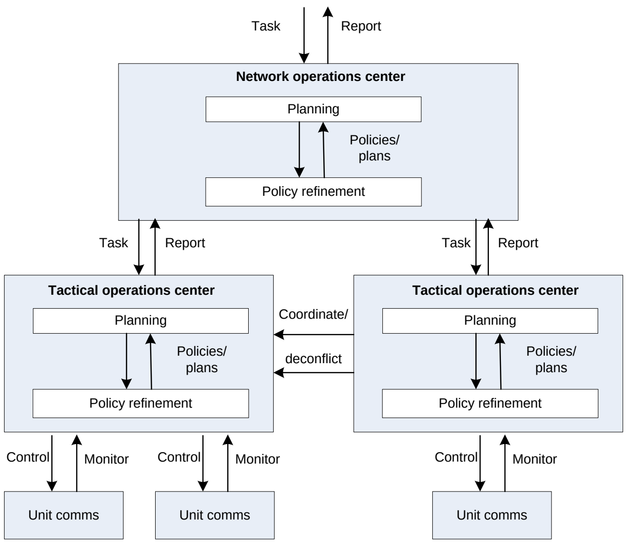

Figure 12: Military OSA Architecture.

Structure shown above enables two basic blocks concerning planning and refinement objectives with control and monitoring of the states of units nodes.

In military applications, the spectrum availability model has several differencies concerning definition of primary and secondary users, mission-oriented planning. Automated design of CR based mobile ad-hoc networks (MANET). The Network Engineering Design Analytic Toolset (NETDAT) was developed to support planning, development, and evaluation cognitive MANET [7]. NEDAT constructs the network topology using heuristic optimization techniques like simulated annealing. Routing bases on the QoS provisioning techniques for mentioned CSMA as well as TDMA (Time Division Multiple Access) techniques. The Automated Design Manager uses the Finite State Machine mechanisms to serve single-snapshot design steps with selection of multiple sets of parameters describing requirements, objectives, topology performances. It consists of a few functional blocks including design modules, neighbor discovery, topology construction, routing, MAC and mentioned ADM. Also OPNET, NS-2 and other tools are shown as possible tools to solve CRN objectives in military wireless networks [7].

Definitions of the critical elements of CRs and policy-based radios are provided by earlier mentioned IEEE Standards Coordinating Committee on Dynamic Spectrum Access Networks (SCC-41) and the Software Defined Radio Forum – Cognitive Radio Working Group (SDR Forum – CRWG). These definitions for the various radio technologies have been integrated by the International Telecommunication Union (ITU) with help from many of its member organizations. The IEEE SCC41 efforts and other activities are described in [11].

The IEEE 802.22 standard is proposed for CR wireless area networks (WRAN) [6]. Three tools define the cognitive functions of Spectrum Manager. The first one is spectrum sensing, the second one is geo-location data-base, and the third one is data-base with information of channels availability. The PHY parameters are optimized in terms of the communication distance.

4.0 CONCLUSIONS

Some new achievements concerning dynamic spectrum management are shown. These are only small excerpt from a very big amount of works concerning solutions especially OSA. Nevertheless such dynamic CRN studies and development, they are still many primary questions concerning DSA tools for CR systems. Some of them are enumerated below.

1) Spectrum sensing and interference environment recognition:

   What interference metrics should be used and what transmission rules could allow operation under a much broader set of transmitter parameters to prevent interference above a particular threshold within a radius of the transmitter?

   The interference metric must be indicative of the impact of the transmitter on the surrounding region. Although the technology for propagation models, inclusive of complex environments, is improving and can provide qualitative results for extrapolation, it is insufficient for quantitative interference analysis. Multiple measurements distributed across the operational area are needed to accurately measure the interference metric. One possible mechanism to obtain multiple measurements would be the development of interference monitoring stations.

2) What are the mechanisms to disseminate the results of the measurements? Would the data be broadcast to all devices or should they be on a request basis?

   The need for assured communications, free from avoidable interference, is a paramount requirement for public safety communications. So the mechanisms for obtaining and releasing spectrum need to be highly predictable. Beaconing is one such mechanism; that is, either a service would send a beacon indicating its using of the spectrum or send a beacon when the band is available for use by another entity. So the basic technical challenge is to create the proper signaling technique.

3) What management policy could provide OSA within heterogeneous wireless military network?
   Technology provides a potential solution to this particular challenge. The recent development of policy-enabled devices can provide assurance that the device can have mechanisms to prevent

operation in unauthorized bands with cognitive adaptation to the dynamically changing environment. Technologists must actively address these concerns. The challenges of employing CRs for the policy community also include that of ensuring secure device operations. Security in this context includes enforcement of OSA rules. As the systems become more and more dynamic, there is an increase in the number of potential interactions between players in spectrum space.

To answer these questions some initiatives concerning OSA are undertaken also in frame of European Defense Agency. CORASMA (Cognitive Radio Spectrum Management) and SETUP (SDR and tactical network Planning & Supervision) are the examples of such activities.

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