INITIAL ASSESSMENT OF PROPOSED COGNITIVE RADIO FEATURES FROM A MILITARY PERSPECTIVE

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Abstract

In this paper we capture generally available theoretical properties, possible technical characteristics and proposed features of the cognitive radio. These features are then subjected to a system engineering based systems definition process and they are divided into user and systems requirements and design features. Then these features are further classified to various effectiveness classes by taking advantage of Hitchins' taxonomy. Thirdly stakeholders are assessed. On the basis of this analysis, the conclusions are presented.

Of the 15 assessed Cognitive Radio features only one qualifies as a design feature and only three as user requirements. When classified by system effectiveness we have one security, one usability, two adaptability and two interoperability features whereas we have 10 performance oriented features. These observations confirm that research and development has been concentrated on performance, especially from the radio engineering perspective.

As the science and art of cognitive radio is still in its infancy, armed forces' materiel and procurement administrations are yet unable formulate exact, measureable and verifiable user requirements for a cognitive radio.

Therefore military materiel, research and development communities would be well advised to continue developing knowledge and understanding of cognitive radio technology.

1. INTRODUCTION

Cognitive radio has been hailed as a next generation evolution from the software defined radio, of which the first commercially available examples are just about to enter the market. Various stakeholders place expectations to cognitive radios from different viewpoints. Regulators and mobile operators are hard pressed for the available bandwidth in the available radio frequency spectrum, thus proposing features like dynamic spectrum access or cognitive spectrum management, military users would need zero-configurable radios that are easy to use and are capable of adapting to different operating modes, including avoiding detection and circumventing jamming, adjusting functional behavior based on the phase of operations, or configurable depending on the geographic region of use, including underdeveloped, degraded and denied operational environments.

Thus the software defined radio establishes the state of the art situation today. In this article we hypothesize that features, capabilities, and characteristics proposed for Cognitive Radio may ultimately be developed into mature expressions of military operational requirements which are satisfied by the Cognitive Radio. By mapping and categorizing contemporary proposed features, we point to areas where technology and user needs are sufficiently mature for quick-wins using cognitive radio technology, and also indicate areas where either further development of the technology or elaboration of the users perception is needed.

As the challenges faced by the United States Joint Tactical Radio System (JTRS) program show, the "requirements creep" can dramatically influence the outcome of any potential cognitive radio development project. Therefore a clear conceptual understanding, categorization of requirements, and matching user needs with the technological possibilities will support eventual successful execution of any such initiative.

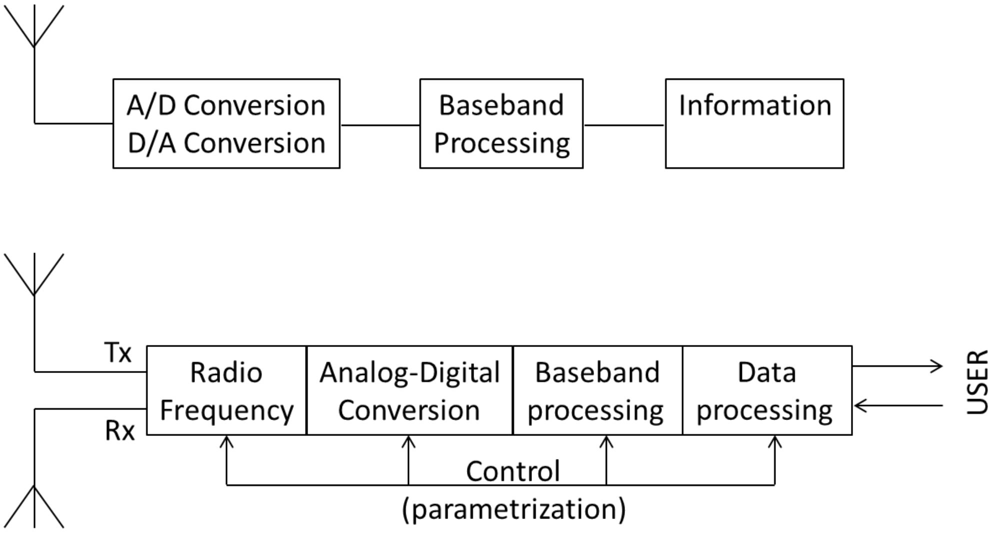
2. FROM SOFTWARE RADIO TO COGNITIVE RADIO

Reference (1) describes cognitive radio (CR) as an evolution from a software defined radio (SDR) and that a CR further develops SDR technologies to support three major application areas, namely:

1. Spectrum management and optimization;
2. Interface with a wide variety of networks; and,
3. Interface with a human and providing electromagnetic resources to aid in his activities

As that definition strongly relies upon the concept of SDR, we shall first take a short look on that concept before we introduce the CR in further detail.

A SDR is a natural development of radio technologies that encompass the advances brought forth by the proliferation of mobile commercial handheld telephony, digital signal processing and software technologies. On the other side, as rapid advances in the digital domain seem to continue to abide by the Moore law, such progress is not as evident in radio frequency (RF) technologies; thus posing technical, functional, and physical upper bounds as to how far SDRs, and subsequently CRs, can evolve in a given situation. In its purest academic form the term software radio refers to reconfigurability of the radio by software. Ideally the transformation of the signal from the RF-domain to the digital domain would take place as close to the antenna as practicable as depicted in figure 1.



Legend:
Tx = transmission, Rx = reception, A/D = analog-to-digital, D/A = digital–to-analog

Figure 1. Pure software radio technological breakdown, above adopted from (2) and below from (3).

However, as already alluded to, a number of physical world issues, as well as component technological challenges, force one to adopt the concept of SDR in a fashion that ultimately is a compromise of available technologies and financial constraints for the design of the radio in question. Furthermore, there are also a number of customer/user (use case) specific limitations that ultimately lead to practical implementations that are, for the time being, quite far from the above figure 1 depicted ideal implementation.(4)

Thereby, influenced by reality in contemporary communication system design, the Wireless Innovation Forum (5) has established, and in concert with other standardization bodies, defined the SDR as:

"Radio in which some or all of the physical layer functions are software defined"

This definition is exemplified in a notional architecture layout as depicted in figure 2. At this point it is important to note that, although some or all functions are software defined, this definition excludes any notion of adaptability or intelligence.

Of course, it is a logical step to introduce some form of adaptability and/or intelligence to a highly capable software defined communications platform. However, the extent to which this would be done bears some comments. The Wireless Innovation Forum recognizes that there may be an intermediate development stage prior to a fully developed CR that they call an Adaptive Radio. By definition this would be a radio / communication system that has the means to monitor its own performance, and then vary its own parameters in order to improve that performance. However, this notion is inherently limited in its capabilities, as it implies a somewhat narrowly focused control loop, which in itself is predefined in its scope and response.

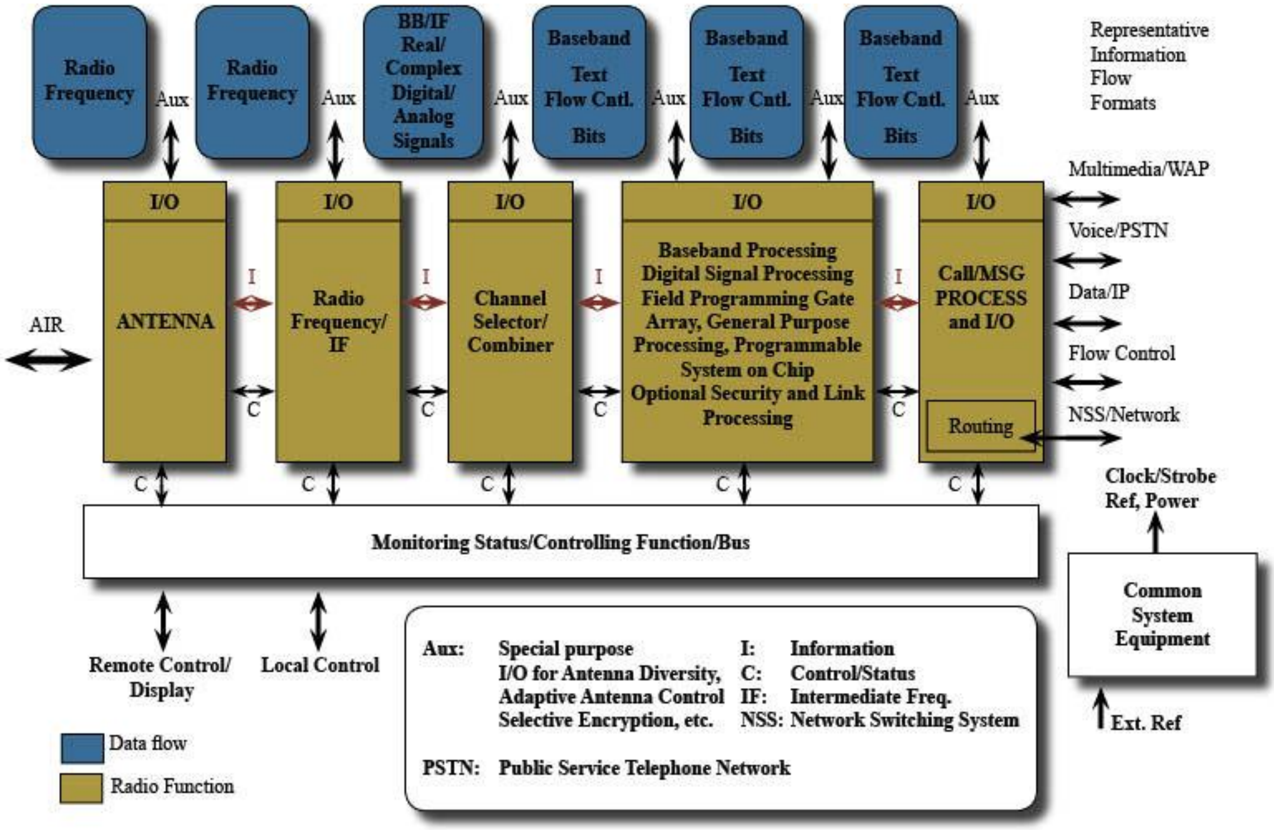


Figure 2. Notional architecture for a SDR. Adopted from (5)

Concurrently, the European Telecommunications Standards Institute, tasked by (6), is also working on the terms and definitions introduced above, most notably via its Reconfigurable Radio Systems Technical Committee (ETSI TC RRS). However, they note that:

> *"The exponential growth in the use of the Internet and mobile communications is placing network resources under stress. This is driving the quest for greater efficiency in spectrum usage through developing technologies. Reconfigurable Radio Systems (RRS) are intelligent radio devices which can sense – and act upon – their environment. For example, they can adjust for location, time, frequency and other users, and they can scan for unused frequency. They thus open up the opportunity for the sharing of unused spectrum amongst multiple services and radio networks, maximizing the use of scarce and expensive frequencies. SDR*

> *and Cognitive Radio are therefore expected to become important drivers for the future evolution of wireless communications and to offer substantial benefits, particularly in the better utilization of the radio frequency spectrum."(7)*

On the other hand, notions like SDR, Adaptive Radio, and the CR, originally coined by (8), have been defined as:

> *"a radio that utilizes SDR, Adaptive Radio and other technologies to automatically adjust its behavior or operations to achieve desired objectives."*(5)

In conjunction with this, the Wireless Innovation Forum (5) used in 2007 the working definition for the CR as:

> *"Radio in which communication 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"*

However, by 2008 the Wireless Innovation Forum was able to agree and formally approve the definition for CR although with caveats that will be explored below in some detail. The terms and definitions for CR from scientific literature, standardization bodies, and other relevant entities were analyzed and (9) came up with a multifaceted definition for the CR:

> *"**Cognitive Radio (as a design paradigm)***
>
> *An approach to wireless engineering wherein the radio, radio network, or wireless system is endowed with the capacities to:*
>
> - *acquire, classify, and organize information (aware)*
> - *retain information (aware)*
> - *apply logic and analysis to information (reason)*
> - *make and implement choices (agency) about operational aspects of the radio, network, or wireless system in a manner consistent with a purposeful goal (intelligent)."*

There are a number of ways that the cognitive radio paradigm can be implemented, thus examples of implementation are presented:

> "**Cognitive radio (as examples of implementation)**
>
> *A radio designed according to the cognitive radio engineering paradigm.*
>
> - *Cognitive radio as defined above that utilizes Software Defined Radio, Adaptive Radio, and other technologies.*
> - *A radio endowed with the capacities: to acquire, classify, retain, and organize information, to apply logic and analysis to information, and to make and implement choices about operational aspects of the radio in a manner consistent with a purposeful goal.*
> - *A radio, radio network, or wireless system designed according to the cognitive radio engineering paradigm."*

Already in 2000 Joseph Mitola III postulated in (8) that these features can be incorporated into an open architecture framework for integrating agent-based control, natural language processing and machine learning technology within a SDR platform; an interdisciplinary approach that still, after a decade since the notion of CR was introduced, merits further attention by the scientific community.

In a SDR the transmission characteristics are defined mostly within the software as an entity called a waveform, and this includes the characteristics that are needed for a successful communication to take place in most of the International Standardization Organization / Open Systems Interconnection (ISO/OSI)-layers. For radio engineering aspects, the ISO/OSI-layers most often addressed, include layers from PHY up to and including LINK and NETWORKING layers. Therefore it is not surprising to note that cognitive features are expected from these layers, or also the waveform.(10) At this point the reader is cautioned that it seems that the terminology applications are diverging, and that issues of civilian context addressed as communication systems are easily labeled in the military SDR domain as waveform issues.

The needed cross-domain design and multi-academic approach is evident, for example in (11) where Virginia Tech's researchers link the awareness/decision making capabilities of the CR with the famous Observe-Orient-Decide-Act -loop (OODA) among other respective cognitive architectures. (Note: OODA-loop was already included in the original seminal article on cognitive radios, e.g., (12)). A number of CR architectures have been proposed and studied, for example in (1,8,9). For our purposes figure 3 will be sufficient as a block diagram.

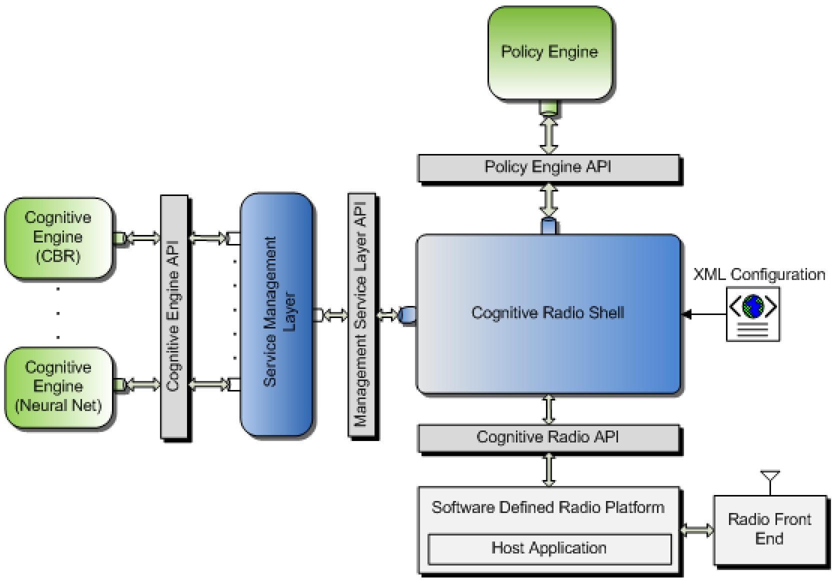


Figure 3. An example of open source Cognitive Radio architecture. Adopted from (13) cf. (14).

This example of a CR architecture highlights the SDR as the platform to execute radio communication services, and furthermore points to the elements needed to provide awareness, reasoning, agency, and intelligence.

3. METHODOLOGY

Modern engineered systems come into being in response to societal needs, i.e., demand, because of new opportunities offered by new technology, or both (15). Demand is, however, recognised as a major source of innovation. In a recent survey of more than 1000 firms and 125 federations by the EU (16) , over 50% of respondents indicated that new requirements and demand are the main source of innovations, while new technology within companies are the major driver for innovations in only 12% of firms (17). Customers influence innovation in three main ways. First, new market opportunities emerge primarily due to changes in customer needs. In addition, introduction of new standards and norms can be seen as a change of customer needs, because governments act on behalf of citizens and customers. Second, the customers' influence in the innovation process. They may be important source of ideas and may assist in the process of new product development or the design of the product. Third, customers' awareness of the benefits of new products is a key factor in determining acceptance of the new product in the market. (16) Demand driven innovation is a specific characteristic in defence, where governments influence the areas in which industry is likely to develop industrial capabilities, because they are the customer and investor, as well as regulator, and in some nations still predominantly the owner (18). This demand driven tendency of innovation is manifested for instance by European Defence Agency (EDA), which declares a "*capabilities based approach*" in development of new military materiel and services (19).

Systems engineering is an established application of systems approach. It can be defined as a "*creative process through which products, services, or systems presumed to be responsive to client needs and requirements are conceptualised or specified, or defined, and ultimately developed and deployed*" (20). Systems life-cycle, in turn, refers to the step-wise evolution of a new system from concept through development, and on to production, operation and finally disposal (15). Different systems engineering life-cycle models, such as waterfall, V- or spiral-model have been developed to facilitate that evolution. In all those models, the first part of the life-cycle deals with capturing, identifying or defining user requirements. User requirements express what users want to do with system. They should be written in the terminology of the problem domain. (21) An example of a user requirement could be: "battalion commander shall be capable of communicating simultaneously to his superiors and subordinates". Next in the process, these user requirements are transformed to systems requirements. They explore the solution, i.e. the system, but should avoid the commitment to any specific design. In other words, they identify what the system will do, but not how it will be done. (21) An example of a system requirement could be: "cognitive radio shall be able to identify jamming automatically". Systems requirements are followed by the systems design part of the process. It clearly defines what is to be built. When it is complete, each design component can be implemented separately by a team who produces it. This means that the design forms the basis for the implementation of a system.(21) These three first process parts of systems engineering life-cycle, depicted in table 1, are called either system definition (20), or system architecting phase, and / or process. In radio engineering a similar breakdown has been proposed for cognitive radios (3).

Category	***Definition***
User requirements (U)	what the users want to do with the system from the operational point of view
System requirements (S)	show what system will do, but not how it will be done
Design (D)	what is to be built

Table 1. First three steps in system definition phase. Adopted from (20)

In addition to the importance of requirements types, it is also essential that different kinds of requirement sub-classes in each requirement type are distinguished. A User or Systems requirement could indicate for instance a functional, e.g., performance related or a non-functional, such as reliability linked need. There is not, however, an agreed taxonomy of these requirement sub-classes. One effectiveness focused classification is provided by Hitchins (22) as illustrated in Table 2.

Category	***Descriptive characteristics***
PERFORMANCE	capability, behaviour
AVAILABILITY	reliability, maintainability
ADAPTABILITY	flexibility, expandability
INTEROPERABILITY	communication, protocol
USABILITY	human factors, man-machine interface
SURVIVABILITY	avoidance of detection, self-defence, damage-tolerance
SECURITY	data, physical
SAFETY	development, operation, maintenance, disposal

Table 2. Classification of system effectiveness. Adopted from (22)

Before beginning the systems definition work, there should also be a good understanding about the stakeholders in order to guarantee that the user needs are identified widely enough. The word 'stakeholder' emphasises the fact that there are usually multiple groups of users (23) . Stakeholder is defined as

> *"participants <in the development process> together with any other individuals, groups or organisations whose actions can influence or be influenced by the development and use of the system whether directly or indirectly"(24).*

A soft systems derived technique applying multiple criteria; Client, Actor, Transformation, Worldview, Owner, Environment, summarized in the mnemonic CATWOE and depicted with its definitions in Table 3, is especially useful for revealing stakeholders and the system description (25),(26).

Component	***Definition***
CLIENT (C)	Those who benefit from what the system produces
ACTORS (A)	Those who carry out the work within the system
TRANSFORMATION (T)	The change which system causes to happen; the process by which an input is changed to a particular output
WORLDVIEW (W)	The perception of the system from a distinct point of view; the assumptions which are made about the system from that perspective
OWNER (O)	The person or organization who has ultimate authority over the system, who can cause it to cease or exist
ENVIRONMENT (E)	What surrounds, or lies outside the system; the system may influence it, but has no control over it

Table 3. CATWOE technique to reveal stakeholders

In the light of all above, this paper studies the proposed features of the CR by following a system engineering based systems definition process and techniques. These features are divided into user and systems requirements, and design features, by using the definitions of different requirement groups. The categorised features are further classified to various effectiveness classes by taking advantage of Hitchins' taxonomy. Thereby stakeholders are assessed with the help of CATWOE –technique. On the basis of this analysis, the conclusions are presented.

4. INTRODUCTION TO PROPOSED COGNITIVE RADIO FEATURES

In this chapter we shall capture a number of potential features, characteristics and capabilities that are associated with the foreseen deployment of CR technology. Grouping and classification of these is based on the principles of (27).

4.1 Dynamic Spectrum Access

Dynamic Spectrum Access (DSA) has been defined by the Institute of Electrical and Electronics Engineers (IEEE) as "the real-time adjustment of spectrum utilization in response to changing circumstances and objectives". (28) For our purposes it is of utmost importance to note that in most reports, studies, and considerations, this approach refers to the fact that national radio communications regulatory bodies have a monopoly position for their national frequency/spectrum assignments within the internationally standardized bounds. Within the position, the bodies consider dynamic spectrum access as mechanisms and procedures for secondary users to use spectrum assigned to the primary user – especially so in the parts of spectrum assigned to commercial use, as depicted in Figure 4. (27)

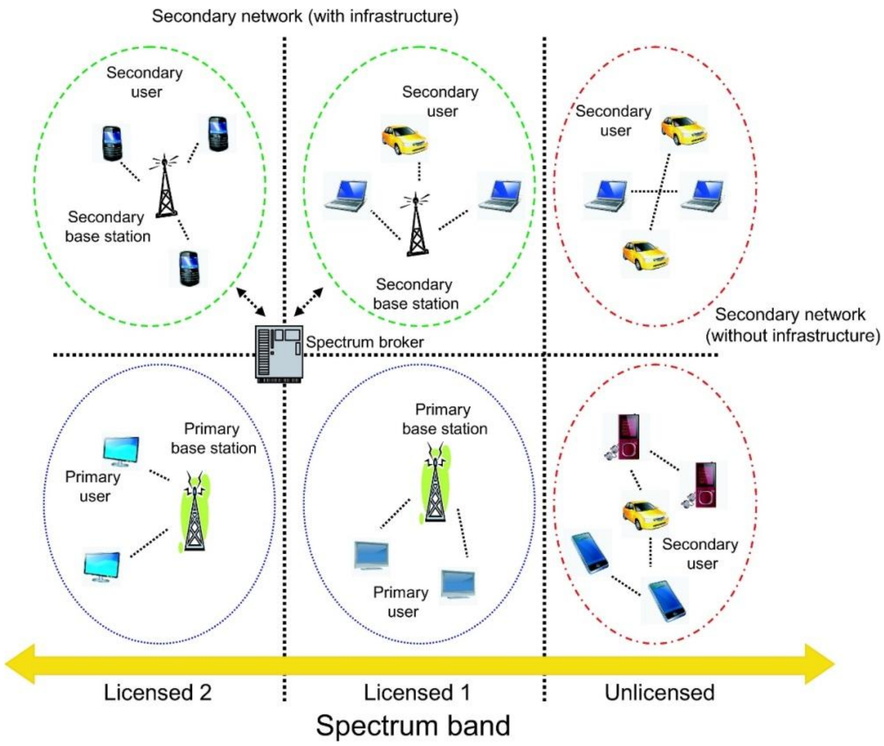


Figure4. A notional example of Dynamic Spectrum Access. Adopted from (29)

Therefore, the definition in itself is well suited for general military needs, but the inferred implementation is not necessarily directly beneficial to military users. In order to realize DSA functions, a CR needs to gain information about its operating environment. Some of the suggested ways to implement this are:

1. spectrum sensing inter alia performing signal detection and classification;
2. utilizing geographical information databases on known emitter characteristics;
3. utilizing pilot channels to distribute environmental information; and,
4. direct information sharing between devices and systems.

The Wireless Innovation Forum (WINNF) cites in (27) that U.S. DoD considers DSA as a critical technology and *"key to adaptive networking",* especially in regard to the spectrum management of various unmanned autonomous vehicles and tactical robots.

Reportedly, implementation of DSA has been shown to improve utilization of spectrum and thereby system performance (27). Whilst this may be true for commercial and civilian environments, the drawbacks, e.g., potentially vulnerable pilot channel, need to be considered for military operational uses separately. On the other hand, many nations face a situation where their national defense forces are more and more squeezed for spectrum within their own nation and that their respective governments would earnestly auction formerly military occupied frequency bands to the highest commercial bidder. Therefore, even though militaries might find DSA to be of minor operational interest in national defense scenarios, DSA definitely is a CR implementation aspect that needs close monitoring.

Although regulator, vendor, and service provider interests in dynamic spectrum access as such may not be of direct interest to military users, the concept of primary and secondary use in conjunction of geolocation awareness, the capability to adjust to frequency management region and broader networking potential, as demonstrated in (30), may yet prove useful to those elements of armed forces that are to be rapidly deployed to worlds crises and hot spots where underdeveloped, degraded or denied access to infrastructure or spectrum might otherwise hamper the successful execution of their mission. Policy questions as to whether the military should enjoy primary user status or be assigned to a secondary user status at different bands of spectrum, is well beyond the scope of this article.

Furthermore, although not directly similar technique to DSA, spread spectrum systems could be developed as overlays that operate concurrently in the presence of legacy narrow-band systems (31) and that by this technique an alternative primary-secondary user mechanism and policy could be developed. For military, such an approach may be interesting in order to avoid hostile interception and jamming.

As already alluded to, DSA research has in many ways focused on secondary uses of spectrum and inherently contains the notion of restricting interference to the primary users. As such, research has shown that many DSA implementations would benefit from various interference avoidance and interference rejection techniques, an issue which in its intentional hostile form is of obvious interest to military. On the other hand, research topics like fairness in spectrum access and spectrum trading issues are not necessarily military main-stream.

4.2 Multiple Antenna systems

Multiple Input Multiple Output (MIMO) smart antenna systems, depicted in Figure 5, are used for enhanced data rate, improved coverage, enhanced system capability or improved link reliability (27). As such MIMO technologies are of interest to military not merely in this stated form but also in degenerated forms like Single Input Multiple Output (SIMO) as well as Multiple Input Single Output (MISO) configurations. Research has shown that all these have potential to improve some aspects of communications system to be of relevant interest and benefit for military users as alluded to in (4) and (30).

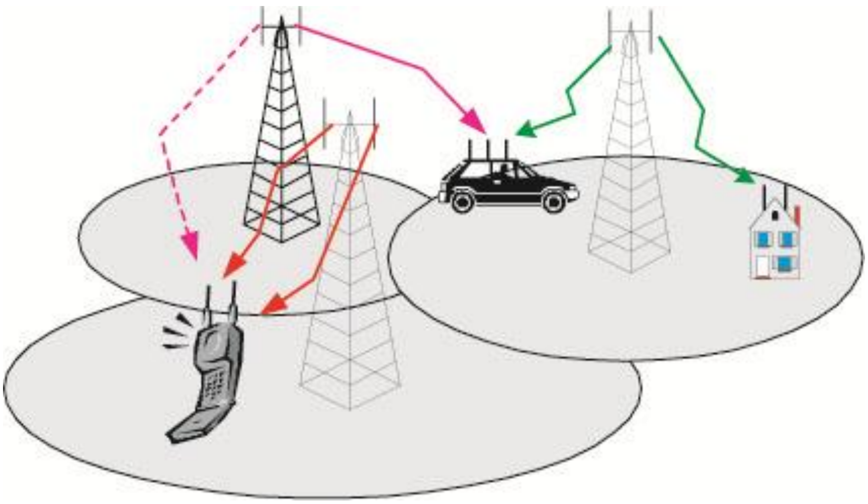


Figure 5. An example of cellular communications system using MIMO. Adopted from (32)

However, the long distances often needed in military communications compel one to use such frequency bands where MIMO-antenna structures are not necessarily easy to implement, at least on a dismounted individual soldier. On the other hand, such structures can be implemented on a vehicle or a platform. Beam forming, spatial multiplexing and diversity coding have all their potential military applications. One of the CR based MIMO applications is to develop a more effective relaying scheme, an area definitely of interest to many military users.

4.3 Radio Resource Management

The process to control radio transmission characteristics at the system level is called Radio Resource Management (RRM). Parameters and characteristics as power, channel, data rate, modulation and error coding are some examples (cf. e.g.,(33)) of controls addressed by RRM in a fashion to optimize the use of limited resources and infrastructure. (27) As such, technologies and mechanisms for interference avoidance, channel/network selection and power control are definitely research areas that are of military operational interest.

4.4 Spectrum Markets

Increased civilian demand for additional bandwidth and spectrum poses a significant threat to military users world-wide. As a "threat", this demand needs to be monitored and military containment strategies need to be developed. Large scale procurement of military CRs (including DSA features) could be justified, and potentially financed, if national authorities were thereby allowed to recoup the revenue from the release of formerly military-only parts of spectrum.

4.5 Single Link Adaptation

At the most rudimentary level a radio engineer needs to consider the quality of service of a communication system is as a single radio link. A number of characteristics and parameters are involved and as such, these considerations are often intertwined with issues assessed within RRM. Mechanisms known as Adaptive Modulation and Control (AMC), Transmit Power Control (TPC), as well as, a number of methods to address Quality of Service (QoS) have been proposed. (27)

4.6 Some considerations on the applicability of commercial market characteristics

WINNF claims that *"in order for wide spread commercial deployment of CRs to occur, new business models need to be generated"* and they continue such an assessment through issues as:

1. improving service of existing systems via cooperative CR techniques;
2. self-organizing networks;
3. enabling access to new spectrum with information services;
4. new wireless revenue models;
5. added capacity to meet bandwidth requirements;
6. improved spectrum access and regional policy management;
7. coexistence of multiple waveforms on a device;
8. better interoperability;
9. reduced cost and size, improved battery life;
10. simplified management and deployment. (27).

The first three subjects may ultimately develop technologies that could be advantageous also in military operations. As technical research and development continues and proliferation of commercial implementations commences supported by adequate standardization, a number of current commercial bottlenecks will be addressed. The range of listed subjects from 5 to 10 is considered potentially important also for military uses.

4.7 Some considerations on the applicability of public safety characteristics

In their analysis of benefits of CR, the Wireless Innovation Forum considers many areas to be advantageous for public safety users (27).

<u>Coverage</u> is always an issue for public safety. In many cases the needed coverage is challenged as for example long distances, missing infrastructure in remote rural areas, or extremely difficult propagation conditions in densely built urban areas, mountainous terrains, and more specifically inside buildings.

Although public safety may in some nations have uniquely allocated frequency bands, natural disasters and major disturbances have shown that such fixed allocations seldom meet bandwidth demand on heavy-load situations. As demand for communication system resources exceeds what is available, an obvious approach would be to prioritize services and traffic. In this aspect a CR may have the potential to support dynamic priority protocols.

Moreover, major disasters and other heavy-load situations also have responding or supporting authorities and agencies that do not necessarily operate specific public safety equipment. Therefore a CR should support interoperable (e.g., legacy) communication services with these entities. Similarly, interoperability could be further enhanced by the deployment of intelligent reconfigurable RF gateways. Role based reconfiguration would support the role of those first at scene and those arriving later, and thus this capacity of the CR itself would better support interoperability with different actors on scene.

Obviously, the information that authorities exchange over the air needs protection. Security of the communication is definitely needed for law enforcement officials, but also to protect the privacy of customers of ambulance, medical, and social services, among others.

Deployed cognitive radios in conjunction with cognitive networks would allow better and more flexible resource management (system as well as device wise) in high-demand situations.

As first responders often arrive on the scene with their own communications equipment, they often do not have access to complementary information services that would be needed for successful mission accomplishment. Thus, the cognitive sensor networking paradigm would potentially provide better on-scene information services, hopefully supported by mechanisms to avoid information overload.

As a summary, most of the characteristics of CR technology needed for public safety services are of interest to military. Such an approach might establish a larger potential clientele for vendors to develop new radio systems, but with one caveat. In some cases the military requirements, although similar to public safety, may actually exceed those for public safety.

4.8 Some considerations on military applications

As with public safety applications the WINNF has also considered potential military applications. The U.S. Army Communications-Electronics Research, Development and Engineering Center (CERDEC) has identified many issues challenging contemporary military communications systems that could be alleviated by the use of CR (34). Among others these include

1. geo-location awareness;
2. automated configuration and near-zero setup time;
3. policy interpretation and adaptive tactical planning;
4. dynamic spectrum management;
5. cognitive antennas,
6. cognitive networks; and,
7. collaborative functions. (27)

Besides these, the unique characteristic of military communication systems, as compared to civilian/commercial systems, is that military communications face the threat of interception, detection and subsequently intentional hostile jamming, and thus have a requirement to be robust enough to sustain operations and communications in spite of those threats.

Whilst a newly deployed military CR could use its DSA and sophisticated RRM mechanisms to circumvent or to protect from hostile intentions over the electromagnetic spectrum, the same would be true in another direction. Either the same device could be devised in a fashion to act as a tactical self-protective jammer or in a more general approach CR technologies could be used for totally new highly automated (potentially distributed/networked) jamming systems. Within these lines of thinking research continues on the subject of cognitive radio against a cognitive jammer introducing completely new sets of possibilities but also challenges.

4.9 Discussion of perceived CR characteristics from military perspective

Obviously the US armed forces presents vendors and manufacturers the largest single customer potential. However, one needs to understand that in her role as the global superpower, the US military is in many ways different from a number of armed forces elsewhere around the world. Let us consider a small-to-mid sized nation committed to the network-centric warfare paradigm (35) , whose defense forces is more aligned towards national defense than expeditionary operations.

First of all, the national defense scenario may allow for the infrastructure of that nation to be used as a national backbone to many of the networked services, at least as long as that infrastructure remains functional in times of crises. Secondly, such a nation may not have air superiority, thus reliance on airborne relaying platforms and mechanisms (e.g., Boeing E-3 Sentry, or SAAB 340 Airborne Warning and Control System-airplanes) would be out of the equation. Thirdly, that nation may not have direct access to satellite services and therefore it would need to solve beyond-line-of-sight communications needs either through its national backbone, or by other radio communications systems.

Furthermore, even within a potential classification of “Military Operational Requirements”, there may be multiple opposing views and stakeholders, e.g., air forces might require near-real-time, broadband, long range line of sight communications services, whereas navies might satisfy similar needs with a relatively narrow-band, beyond-line-of-sight services where the range is an issue. Furthermore, the national defensive needs for a small-to-mid sized landlocked nation may be quite different from those of a global superpower. Therefore, the reader is cautioned that although we shall use the generic term military operational requirements, this label in itself is indeed not a uniform one!

On the other hand, such nations often participate to international military operations where issues like spectrum management and interoperability come into question. Furthermore, especially in Europe, the defense expenditures have been on the decline and it would be safe to assume that replacing legacy systems with new CRs in single procurement/deployment would be unreasonable. Reducing manpower, and thereby personnel costs, will place a challenge on military procurement, especially as such reductions are often covered by remotely operated sensors, intelligent weaponry, unmanned vehicles, and robotics. Therefore, in addition to joint and coalition operations, such a nation would need to be capable of operating legacy systems side by side with new technology for some significant periods of time exacerbating the need for functions that support interoperability. Moreover, the hostile intent against a nation’s military radio communications has already been alluded to, thus reliance on commercially available civilian solutions should be treated with care.

Although figure 2 presented the CR as an add-on to a SDR, and that the CR itself may include one or more waveforms, such functional separation would be extremely difficult to perform, especially if considered from systems engineering perspective. As we do not yet have deployed CR systems, on top of which to develop new services and/or waveforms, we shall assume that first generation CRs will be specifically developed to meet chosen waveforms that are to be operated on specific hardware, thus, by definition such a CR will be capable of transferring duty traffic from one waveform to another, based on the capability of situational awareness it develops, along with decisions it takes.

5. CLASSIFICATION AND CATEGORIZATION OF PROPOSED COGNITIVE RADIO FEATURES

Obviously ingenuity of research has already presented numerous alternative approaches and features for cognitive radio of which only major categories were presented in the previous chapter. In this chapter these categories will be assessed as described in methodology presented in chapter 3. Summary of analysis in this chapter is presented in a chapter 6 discussion.

5.1 Spectrum sensing, performing signal detection and classification

Spectrum sensing, performing signal detection, and classification can be considered relatively straightforward radio engineering issues, at least from the perspective that the problem space is defined, where technologies mainly do exist and metrics can be developed (36). As a new capability we can safely consider this feature to have potential for a system requirement and that it relates to the performance category under Hitchins's classification (22).

We also observe, according to the CATWOE technique, that clients (C) of spectrum sensing, signal detection and classification would be military end users and military mid-level management, whereas military end-users are also obvious actors (A). Operational users potentially benefit by: the ease of use; improved reliability; and quality of service. Moreover, especially in the military domain, tactical/operational level network and frequency management and planning, and ultimately their use, may become somewhat easier by these features. Thus the potential benefits represent the expected Transformation (T). Generally the worldview (W) to be chosen could differ between aforementioned armed forces of a small-to midsized nation in national defense scenario and a superpower preparing for rapid deployment anywhere on the globe. However, this feature can be implemented in a coherent manner where the chosen worldview does not necessitate any dramatic differences in implementation. But selecting either worldview may have other consequences. Obviously there is a difference from a vendor perspective whether the owner (O) of the system would be a small national defense or a global player. Otherwise, spectrum sensing issues need not have differing environmental (E) aspects based on the worldview selection as long as the smaller player prepares to deploy to coalition operations in areas beyond national defense scenario.

5.2 Awareness, decision making and selection of waveform, network, channel and other spectrum use related characteristics

Awareness and decision making as features of a CR are somewhat challenging to define, as these need new measures and metrics that are not part of everyday practice within materiel procurement and acquisition offices (33,37). However, such metrics can be developed, thus leading these features at this level to be assigned to the system requirements category. Although these features may eventually influence performance, interoperability, and even survivability, the very essence of these features is adaptability under Hitchins's classification (ibid.). Our assessment of this feature through the CATWOE technique is the same as conducted in previous chapter 5.1 but complemented by noting that the transformation (T) would be related to reliability, availability and quality of service of a radio communications related to the CR.

5.3 Geo-location awareness

Geo-location awareness of a CR can be implemented in a variety of ways. The CR could, pending on processing power, concurrently run tactical or global positioning waveforms to perform this function, or it could use geographical information databases on known emitter characteristics as examples of implementation.

Metrics for CR's geo-location awareness can be relatively easily defined. However, the question of the use of this geo-location awareness capability of the CR with its associated services within it, or being eventually utilized by the end user, may affect our consideration of should this capability align to a user or a system requirement. As our focus in this article is on the CR, we shall consider this feature as a system requirement. Nevertheless, this feature is obviously performance related. Our CATWOE assessment of this feature is basically the same as in section 5.1, but with a caveat that depending on the worldview selection, a smaller customer may choose to adopt smaller databases, shorter position data formats, smaller map areas to be stored, etc. That customer may choose to do this in order to improve other communication reliability parameters, battery life, or even device's physical size (cf. Link-11 and Link-16 formats for position data). Thereby, we conclude that within this feature, the worldview selection may have a significant impact on implementation. Furthermore, use of this feature could affect the reliability, availability and quality of service of radio communications of the CR in question and being thus considered also as transformational (T) in character.

Reader is advised that source (27) references studies that promote using pilot channels to distribute environmental information. Environmental information can be geo-location related but also include awareness through features like those described in 5.1 and 5.2. Although pilot channels may be appropriate for civilian communication standards, they may be harmful and dangerous in military context due to possible exploitation.

5.4 Enhanced data rate, improved coverage, added capacity to meet bandwidth requirements, improved link reliability, Quality of Service, and enhanced system capability

Data rate, coverage, et al., are already general metrics of a radio communications systems. Although these directly translate to military operational users' easily understood needs, they qualify in our assessment as a potential system requirements that fall under the category of performance. Our assessment of these features through CATWOE technique is the same as conducted in previous section 5.1 with the caveat that worldview selection may ultimately lead to or constrain the possible solution waveform or communication standards which contribute to satisfying the requirements of these metrics.

5.5 Improved spectrum access and regional policy management, dynamic spectrum management, access to non-allocated frequency bands, policy interpretation and adaptive tactical planning

Spectrum access and policy management are clear system requirements that do need further elaboration to clearly establish measurable metrics. These features, although close to adaptability, performance and interoperability, are important elements that impact desired performance. Our CATWOE assessment follows previously established guidelines with the difference being that the principal client for this feature would be military mid-to-high military operations planning and management with high-level procurement and acquisition offices being lesser or secondary beneficiaries.

5.6 Direct information sharing between devices and systems

A proposed new mechanism, direct information sharing between devices and systems, has been presented as a feature that further facilitates the implementation of DSA, as well as, novel cognitive network solutions. This concept may refer to the radio spectrum and network related information (4) a CR would need to maintain environmental awareness, and thus, continue executing appropriate decision making processes. Unless this feature is appropriately designed, it may become a dangerous feature, similar to the vulnerability described with regard to pilot channels. On the other hand, if this feature takes security concerns into account, it may prove to be very useful indeed. Once the information requirements of awareness and decision making processes have been defined as posited in section 5.2, this feature can be defined in a relatively straightforward manner and metrics can be established. As such, this feature would fall into a system requirement category. At a system level this feature bears some linkages to system effectiveness categories like: performance, availability, and adaptability; but, ultimately information sharing is a question of interoperability. Our CATWOE assessment is similar to that of section 5.1.

5.7 Coexistence of multiple waveforms on a device, radio resource management (incl. AMC, TPC)

Coexistence of multiple waveforms on a device is an already existing feature of contemporary SDRs including rudimentary implementation of RRM functions. Therefore, we shall focus in this on RRM. RRM may have inherent functions to operate and manage internal hardware of the CR, but a more advanced RRM function would also execute similar functions over the air-interface as already implemented in some base stations compliant to the 3rd Generation Partnership Project (3GPP) specifications. RRM, as such, does not have any direct reference in the industry de-facto standard for SDRs, or the Software Communication Architecture (38) ; but it may have been implemented in vendor specific manner. A typical case would be the Core Framework, as an element in a SDR operating environment, to probe radio hardware for available resources to execute intended waveform. Unfortunately, such implementations are company proprietary information, and thus not open to public. By the very nature of these features, we can conclude that they are potential system requirements that are linked to availability, adaptability and interoperability but are to be ultimately categorized into the requirements classification of performance. Our CATWOE assessment is similar to that of section 5.1 with the caveat that these combined features will transform the way communications and data flows are relayed from one network to another, and thus, facilitate new network paradigms.

5.8 Interference avoidance and interference rejection techniques

Interference avoidance and rejection techniques have been researched from the secondary spectrum use perspective and that research has brought forward interesting new techniques in the area. Some of these may also have military applications (see e.g. (39)). These kinds of features rank as potential lead-in to subsequent system requirements, and although linked to availability and survivability, are inherently performance related. Complementing our baseline CATWOE assessment of section 5.1 we note that these techniques could affect reliability, availability and quality of service of a radio link and thus can be considered as the transformational (T) for the military user.

5.9 Advanced antennas, beam forming, spatial multiplexing, diversity coding

The application and potential benefits of various advanced antenna technologies has already been discussed. An antenna sub-system may in some cases be considered a system requirement, but we shall consider this within the category leading to a design requirement. Various antenna structures have been proposed (see e.g., adaptive antenna array in (4) pp.36-42), and their characteristics are relatively well known insomuch as to enable the use of measurable metrics and thus facilitate detailed requirements specification. Depending on the motivation to deploy these, such features could be categorized as sub-classes of adaptability, availability, or survivability. Since our main focus in this article is to consider potential CR features from a military perspective, this feature shall be categorized into the sub-class of performance. (See also below for related jamming)

These features benefit operational end users potentially by the improved reliability of communication including low-probability of detection and interception, improved range, and, improved availability of communication service in hostile environments equaling the desired transformation (T). Thereby, the beneficiary and customer (C) would definitely be the end-user and of course his direct superiors, i.e., military commander of that operation. Otherwise our CATWOE analyses follow that of presented in section 5.1 with a note that the environment (E) needs to be considered for each use case separately.

5.10 Service and traffic prioritization / self-organizing networks

As far as traffic prioritization is concerned, we must consider at least three distinct types of traffic: firstly, end-user traffic, coming from outside source into the radio to be communicated by radio waves (and vice versa); secondly, incoming radio traffic that needs relaying back to another radio; and, thirdly, inter-radio information sharing as already addressed in section 5.6

In the first case, before the advent of automated data processing and digital communication systems, traffic prioritization was routinely conducted by the assignment of different levels of authority to various levels of military command personnel, including multiple categories of message priority types. The second and third cases are related to networking issues. Prioritization could eventually be developed into a satisfactory user requirement, but due to the networking aspects, we shall consider these as <u>system</u> requirements. Although they may have links to usability and availability, prioritization is clearly a <u>performance</u> oriented feature (40). Furthermore we posit that CATWOE assessment in section 5.1 will fit this category too.

5.11 Better interoperability / cognitive RF gateways

Interoperability is a system characteristic. Armed forces and military alliances have for some years already conducted exercises and other testing events like Coalition Warrior Interoperability Demonstration, or Combined Endeavour, to test if participants' systems meet this objective. Interoperability is a military objective that our armed forces' transformation after early 90's revolution in military affairs (41) and network enabled paradigms (35) push forward. As such, it is relatively mature statement of <u>user</u> requirement and in Hitchins's classification (22) is obviously an aspect of <u>interoperability</u> by itself. This objective is independent of the worldview (W) differences alluded to earlier, as long as, all actors are expected to participate in joint combined operations. Beneficiaries are military end users, mid-management, procurement offices, and high level commands, so we can put it simply: the customers, actors and owners (C, A, O) of these features are armed forces as a whole and internationally. The major transformation (T) to arise militarily from interoperability at the radio level is the change in tactics: no longer is international coalition interoperability limited to fixed line communication systems at divisional HQ level. Contemporary operations have already witnessed mixed multinational forces well below company level utilizing and benefitting from this aspect. Coalition forces can be mixed at various unit levels, company of A-nation within a battalion of B-nation may be granted tactical control of a platoon of C-nation, while still being assured that command function can be performed utilizing interoperable communications systems. Another transformation is within tactics in a sense that one no longer needs to assign rigid areas of operation along the nationalities grouping of the coalition forces. These changes in the practice of war fighting ultimately facilitate command and control in original environments as derived through the worldview above, but also facilitate operations in new and demanding yet underdeveloped, degraded and denied operational environments.

5.12 Role-based reconfiguration, automated configuration and near-zero setup time, simplified management and deployment.

Automated yet role-based configuration of radio networks and their parameters, potentially rapidly in conjunction with deployment, is a feature that military operations planning and signals officers have long been expecting, which leads us to consider this as a <u>user</u> requirement that can be further considered linked to performance, but more as a usability issue. Clients (C) for this feature are obviously the military operational planners and signals officers, whereas the latter would also be the actors (A). The transformation (T) this feature would bring about would be rapid deployment and improved interoperability; which both, on their part, support successful mission accomplishment. Considering this feature, the previously postulated worldview does not need to change. Although the baseline consideration for the environment (E) is still valid, this feature can be viewed as an improvement in military capability to deploy to underdeveloped, degraded and denied environments.

5.13 Security, circumventing hostile jamming, tactical self-protective jamming

Military CR shall be deployed to hostile, denied, environments, and as such, they need to have appropriate capabilities to protect the users, the radio signal, and the information they transmit(42-44). Furthermore, these need to be accomplished under hostile jamming. As a new capability, CR, as far as we consider them mainly communication devices, could also include some countermeasure capabilities, e.g., tactical self-protective jamming. In the SDR environment, these would be normally considered as features of the waveform or multiple waveforms, but CRs (including cognitive networks), could bring novel approaches to the implementation of these features. However, the weapon - counter-weapon cycle will also eventually emerge in this area, thus leading to CR against cognitive interception/jamming scenarios (42). For military acquisition and procurement, there would be little incentive to embark on a CR procurement process unless they incorporate these features. Thus we can consider these features as user requirements that obviously fall into the security category in the system effectiveness classification. As these features ultimately either jeopardize or support successful mission accomplishment, the customer (C), and ultimately the main beneficiary of these features, is the military operational commander, whereas end-users and signals officers are actors (A).

5.14 Reduced cost and size, improved battery life

Users everywhere, regardless whether they are civilian or military, are concerned about the cost and size of their devices, as well as of their battery life. As such we deem these features as user requirements that are directly performance related. In the military domain, the customer (C) and actor (A), would be logistics and materiel administrations. The transformation (T), via these features, if successfully implemented, would facilitate durability in use; portability for soldiers on the ground; as well as, ease of maintenance and installation onboard space, power and heat limited platforms. Otherwise our baseline for worldview, owner and environment are sufficient.

5.15 Fairness in spectrum access / spectrum trading and markets / new wireless revenue models

By definition, for what is ultimately to be built, these features seem to be design requirements that are linked to availability aspects, but fit better into the systems effectiveness category of adaptability. Customers (C) of these features would be the spectrum regulator, vendors, as well as, network service operators, where the end-user’s role would be considered as an actor (A). These features would change the way spectrum is used today. This transformation (T) will ultimately facilitate primary and secondary uses of spectrum, initially in commercial domain, potentially expanding to public safety first, and ultimately, challenging the remaining military specific spectrum. The worldview (W) of these features is that of a commercially driven, but government regulated, civilian end-customer access to ubiquitous broadband communications whenever and wherever desired. The owner (O) of these features is the spectrum regulator and the environment (E) is civilian.

A summary of the analysis of this chapter on proposed Cognitive Radio features is presented in table 4.

TABLE 4: A Summary of Analysis of Proposed Cognitive Radio Features

Offered CR features (numbers indicate sections above)	System Definition	System Effecti-veness	Customer (C)	Actor (A)	Transformation (T)	Worldview (W)	Owner (O)	Environment (E)
5.1 Spectrum sensing, signal detection and classification	SYSTEM	PERF	MIL: *end-user *mid-mngmnt	MIL: *end-user	Ease of planning, mgmt., use	a)natl.defence+ expeditionary ops b)superpower global ops	Military in general	See (W)
5.2 Awareness, decision making, param selection	SYSTEM	ADAPT	See 5.1	See 5.1	Reliability, availability and QoS	See 5.1	See 5.1	See 5.1
5.3 Geo-location awareness	SYSTEM	PERF	See 5.1	See 5.1	Reliability, availability and QoS	See 5.1, note: Selection of (W) may affect implementation	See 5.1	See 5.1
5.4 Enhanced data rate, coverage, capacity, link reliability, QoS	SYSTEM	PERF	See 5.1	See 5.1	See 5.1	See 5.1, note: selection of (W) affects waveforms to be implemented	See 5.1	See 5.1
5.5 Spectrum access, policy management	SYSTEM	PERF	*ops planners *acquisition offices	See 5.1	See 5.1	See 5.1	See 5.1	See 5.1
5.6 Information sharing	SYSTEM	INT.OP	See 5.1	See 5.1	See 5.1	See 5.1	See 5.1	See 5.1
5.7 Multiple waveforms, RRM	SYSTEM	PERF	See 5.1	See 5.1	Facilitates new networking paradigms	See 5.1	See 5.1	See 5.1
5.8 Interference avoidance and rejection	SYSTEM	PERF	See 5.1	See 5.1	Reliability, availability and QoS	See 5.1	See 5.1	See 5.1
5.9 Advanced antennas, beam forming etc.	DESIGN	PERF	Op CDR	See 5.1	LPD/LPI	See 5.1	See 5.1	See 5.1, note: each use case
5.10 Service and traffic prioritization / self-organizing networks	SYSTEM	PERF	See 5.1	See 5.1	See 5.1	See 5.1	See 5.1	See 5.1
5.11 Interoperability / cognitive RF gateways	SYSTEM	INT.OP	MIL generally	MIL generally	New tactics: mixed composition forces, flexible AOO/AORs	See 5.1	See 5.1	See 5.1
5.12 Reconfiguration, near-zero setup	USER	USAB	*Ops planners * signals officers	Signals officers	Rapid deployment, Interoperability Improved capability to deploy to under-developed/denied env	See 5.1	See 5.1	See 5.1
5.13 Security, circumventing hostile jamming, tactical self-protective jamming	USER	SECUR	Op CDR	End-users Signals officers	Mission accomplishment	See 5.1	See 5.1	See 5.1
5.14 Cost, size, battery life	USER	PERF	Logistics Materiel administration	Logistics Materiel admins	Durability, Portability Constrained platforms	See 5.1	See 5.1	See 5.1
5.15 Spectrum trading, markets, revenue models	DESIGN	ADAPT	Regulator, Vendor, Network Service Operator	End-user	Paradigm shift in spectrum use Note: threats to MIL spectrum	Gov. regulated, commercially driven civilian access	Regulator	Civilian

6. DISCUSSION

One of the main drivers for cognitive radios is the need to satisfy ever increasing demand for bandwidth in the commercial civilian domain. DSA and novel spectrum utilization mechanisms are intensively being researched from the radio engineering perspective, but what cognition methods for the end user, what benefits from additional cognition, what capabilities are realized, and how cognition can be applied to other applications, like cognitive radar, have not been addressed in sufficient detail (45), and this research can only reaffirm this claim.

Of the 15 offered CR features, only one qualifies as a design feature, and only three as user requirements. When classified by system effectiveness, we have one security, one usability, two adaptability, and two interoperability features, whereas we have 10 performance oriented features. These observations confirm that research and development has been concentrated on performance, especially from radio engineering perspective.

When applying soft systems methodology through CATWOE technique we find that the worldview (W) may have a significant impact on how a feature should be developed and implemented. Since most of the features are performance oriented, it is no surprise that many of the expected transformational outcomes are defined in terms of communications parameters and metrics like reliability, availability, or quality of service. However, the category of transformation also reveals the drivers and motivation to proceed further with research and development for a specific military cognitive radio; namely it facilitates changes in tactics and new ways to deploy the CRs themselves, as well as, forces on the ground, that further support timely mission accomplishment, with lesser number of casualties or instances of collateral damage.

Our analysis also points to diverging markets. DSA, new spectrum access mechanisms and new trading and revenue models, will most probably drive the civilian / commercial telecommunications industry in directions that are non-aligned with military objectives; and may, actually be contrary to military interests. New spectrum markets and trading, as well as, new revenue models, seem at the moment irrelevant from the armed forces' perspective, although one has to admit that some new useful innovations, services, or approaches to spectrum management may eventually arise from these concepts.

CR as a concept is not yet mature enough so that waveform, radio (as an independent device) or network could be planned, designed, developed and implemented as independent entities. Therefore, at least first-generation CRs, including aforementioned elements, need to be designed using a holistic systems-engineering approach. Ultimate design and implementation shall require more cross-domain, multi-discipline research, efforts and investments.

As the science and art of CR is still in its infancy, armed forces' systems engineers, signals corps, materiel, and procurement administrations, are as yet unable to formulate exact, measureable, and verifiable requirements for a CR.

Radio communications range, bandwidth, power, etc., are easily measured metrics whereas cognition is, at least within military signals corps and materiel administration, not easily specified. Some metrics can be developed for situational awareness, e.g., is the radio aware of other signals' presence. Some pre-established policies, although context-related, can be developed to guide the subsequent decisions of the CR. However, challenges for the requirements management of <cognition> increase when one moves further away from waveform, from radio device towards the network and infrastructure type considerations.

Therefore military research and development communities as well as armed forces' materiel administrations, would be well advised to:

- continue developing knowledge and understanding of CR technology in general and proposed features in specific;

- initiate activities that translate CR features into potential advantages and benefits in military use cases, i.e., to start the process to draft initial military requirements for CRs; and

- utilize modern iterative development models that enable the development of competencies, understanding, and, implemented capabilities in a balanced manner.

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