NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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**STO TECHNICAL REPORT** **TR-IST-077**

# Cognitive Radio in NATO

(La radio cognitive au sein de l'OTAN)

Findings of Task Group IST-077.

Published January 2014

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# The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses

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# List of Acronyms

| | |
|---|---|
| AJ | Anti-Jamming |
| BFT | Blue Force Tracking |
| CDSA | Cooperative Dynamic Spectrum Access |
| CN | Cognitive Network |
| COI | Community of Interest |
| CR | Cognitive Radio |
| CRC | Communications Research Centre Canada |
| CRN | Cognitive Radio Network |
| DGA | Délégation Générale pour l'Armement |
| DSA | Dynamic Spectrum Access |
| ECM | Electronic Countermeasures |
| EOB | Electronic Order of Battle |
| ESM | Electronic Surveillance Measures |
| EW | Electronic Warfare |
| FKIE | Fraunhofer-Institut für Kommunikation, Informationsverarbeitung und Ergonomie |
| FMSC | Frequency Management Sub Committee |
| LPD | Low Probability of Detection |
| LPI | Low Probability of Interception |
| MANET | Mobile Ad Hoc Network |
| NARFA | National Allied Radio Frequency Agency |
| NATO | North Atlantic Treaty Organization |
| NCO | Network-Centric Operations |
| NCW | Net Centric Warfare |
| NEC | Net Enable Capability |
| NJFA | NATO Joint civil and military Frequency Agreement |
| OODA | Observe, Orient, Decide, Act |
| RMA | Royal Military Academy |
| RTG | RTO Task Group |

| | |
|---|---|
| SMB | Spectrum Management Board |
| | |
| TCS | Thales Communications & Security |
| TFMC | Theatre Frequency Management Cell |

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# Cognitive Radio in NATO

## (STO-TR-IST-077)

# Executive Summary


In national operations, spectrum congestion is not usually a significant concern. However, in multi-national and coalition operations, the spectrum must be carefully managed to allocate channels to all participants. The demands on the spectrum are generally larger than the resource can support in these conditions, and each nation must operate with very limited access. However, while the entire spectrum is allocated, it is not all in use at all times.

In NATO, frequency management is based on a static allocation of spectrum bands and frequencies. While this is effective for interference avoidance and is necessary for some spectrum users, including many legacy systems, it prevents dynamic reuse of allocated bands that are not in use. For modern radio systems that are more tolerant of interference, a more effective spectrum access strategy would allow radios to adapt their operating frequencies in response to the changing propagation and interference environment. This strategy is the basis of the Cognitive Radio (CR) technology concept.

A more dynamic approach to spectrum access, as provided by CR technology, is expected to bring a number of benefits, in particular, more effective use of spectrum to increase usable bandwidth in congested theatres of operations. This should provide increased robustness to dynamic conditions, but does not mitigate the need to increase the spectrum efficiency of future systems.

The objectives of this NATO RTG were to review and synthesise the R&D in CR technologies for military applications, and to investigate the technology and its implications for future NATO operations.

This NATO RTG has focused on the coexistence of coalition tactical networks operating in the same theatre of operations, i.e. cognitive radio networks that are not centrally coordinated. This is considered to be an important factor in the successful introduction of this technology into the coalition theatre that is not being considered elsewhere.

Technical contributions within the RTG included numerous possible solutions for addressing more effective use of the spectrum resource. These contributions demonstrated the need for a common framework to provide a fair basis to compare different CR solutions in realistic simulations of operational scenarios.

To this purpose, the group has started to develop a new simulation methodology, based on the operational vignettes produced previously by NC3A. The chosen vignette considers preventing the hijacking of an aid convoy within a multinational coalition context, but the methodology can be applied to any of the current or future NATO vignettes. The methodology provides a framework to compare CR solutions, based on how capable they are to support a range of services, such as voice, data and video.

The simulation methodology takes a theatre-wide view of spectrum use. Interference from one network may impact the capability of a nearby network; this needs to be considered in the evaluation of the technology. To this end, the simulation approach considers the impact of spectrum use by each network on the others nearby, and considers the successful provision of necessary services within all networks simultaneously.

This report includes the recommendations of the RTG, including steps that should be taken by NATO spectrum planners, as well as directions for the subsequent RTG, IST-104-RTG-050, “Cognitive Radio in NATO-II”, which started in January 2012.

# La radio cognitive au sein de l'OTAN

## (STO-TR-IST-077)

# Synthèse

Lors d'opérations nationales, l'encombrement du spectre ne constitue pas une inquiétude majeure mais lors d'opérations multinationales ou en coalition, le spectre doit être soigneusement géré pour affecter des canaux à tous les participants car les demandes sur le spectre sont généralement plus importantes que ce que la ressource peut fournir dans ces conditions et chaque nation doit pouvoir opérer avec un accès très restreint. Néanmoins, bien que l'intégralité du spectre soit allouée, il n'est pas constamment utilisé à 100%.

Au sien de l'OTAN, la gestion des fréquences est basée sur une affectation des bandes et fréquences du spectre. Tandis que cette gestion est efficace pour éviter les interférences et est nécessaire pour certains utilisateurs du spectre disposant de nombreux systèmes non agiles, elle empêche la réutilisation dynamique des bandes affectées qui ne sont pas en cours d'utilisation. Pour les systèmes radio modernes qui tolèrent mieux les interférences, une stratégie d'accès plus efficace au spectre permettrait aux radios d'adapter leurs fréquences d'utilisation en fonction des modifications de la propagation et de l'environnement d'interférences. Cette stratégie est à la base du concept technologique de radio cognitive (RC).

Une approche plus dynamique de l'accès au spectre, comme le propose la technologie RC, fournirait de nombreux avantages, en particulier une utilisation plus efficace du spectre pour augmenter la bande-passante utilisable sur un théâtre d'opérations encombré. Cela devrait donner une robustesse aux environnements dynamiques mais n'atténue pas pour autant le besoin de développer davantage une efficacité accrue d'utilisation du spectre par les futurs systèmes.

Ce RTG de l'OTAN avait pour objectif, d'une part, d'examiner et résumer l'état de R&D des technologies RC en vue d'applications militaires et, d'autre part, d'étudier cette technologie et ses implications pour les opérations OTAN à venir.

Le RTG s'est focalisé sur la coexistence de réseaux tactiques de la coalition au sein du même théâtre d'opérations, à savoir, des réseaux de radio cognitive noncoordonnés ; ce facteur est considéré comme important pour le succès de l'introduction de cette technologie sur le théâtre de la coalition, qui n'a pas encore été étudié.

Les contributions techniques du RTG comprennent de nombreuses solutions possibles visant à mettre en œuvre une utilisation plus efficace de la ressource spectrale. Ces contributions ont démontré l'existence d'un besoin d'établir un cadre commun de sorte à fournir une base égale pour comparer les solutions différentes de RC proposées par des simulations réalistes de scénarios opérationnels.

À cette fin, le groupe a commencé à développer une nouvelle méthodologie de simulation, fondée sur les scénarios opérationnels produit par la NC3A. Le scénario choisi met en scène un convoi d'assistance médicale à protéger contre des tentatives de détournement dans un contexte de coalition multinationale mais la méthodologie peut être appliquée à tout autre scénario OTAN actuel ou futur. Cette méthodologie fournit un cadre pour comparer les solutions de RC en fonction de leur capacité à fournir un éventail de services comme la voix, la vidéo et l'échange de données.

La méthodologie de simulation envisage une utilisation du spectre sur l'ensemble du théâtre. Les interférences d'un réseau peuvent avoir un impact sur les capacités d'un réseau voisin : cela doit être pris en compte lors de l'évaluation de la technologie. Dans ce but, la simulation envisagée prend en compte, d'une part, l'impact de l'utilisation du spectre par chaque réseau sur les autres réseaux voisins, et d'autre part, la fourniture simultanée des services nécessaires à tous les réseaux.

Le présent rapport inclut les recommandations du RTG, comprenant les mesures à prendre par la planification OTAN d'emploi du spectre ainsi que les orientations pour le prochain RTG, IST-104-RTG-050, « La radio cognitive au sein de l'OTAN - II », qui a débuté en janvier 2012.

# Chapter 1 – INTRODUCTION

In the recent years wireless communication has suffered from frequency spectrum scarcity, as newly developed techniques always demanded an additional exclusive spectrum access. Nevertheless, the utilization of the assigned spectrum still only ranges between 15% and 85% [1]. Some measurements have been performed in Brussels at the Royal Military Academy (RMA) in 2008. Figure 1-1 reveals a typical utilization of roughly 24% in the 30-1300 MHz frequency band. It can be seen that, although all the frequency bands are allocated, the spectrum utilization is far from being optimal. The same goes for the military frequency bands. It can be seen on the figure that the NATO harmonized UHF frequency band from 225 MHz up to 400 MHz is hardly used.

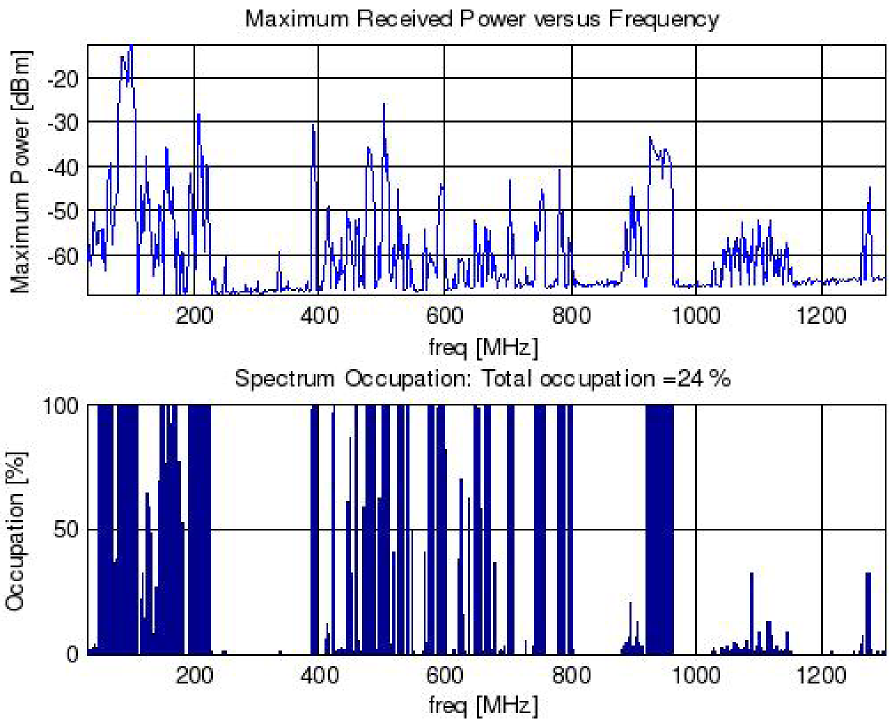


**Figure 1-1: Frequency Utilisation in the 30-1300 MHz Frequency Band (top) Maximum Power Versus Frequency, (bottom) Spectrum Occupation in % of Time.**

Today's frequency regulation is almost always based on a static allocation or licensing of frequencies. Due to this static and inflexible allocation, legacy wireless systems have to operate only in a dedicated spectrum band and cannot adapt the transmission band according to the changing environment. The major factor that leads to this inefficient use of radio spectrum is the spectrum licensing scheme itself. The procedure is laborious and hence once a system has obtained a frequency band, it will not let go of it. Therefore, it is important to present alternatives to the current licensing scheme, as well as to present alternatives to the current spectrum management structures and processes.

Also in NATO the frequency management is based on a static allocation of spectrum bands and frequencies. In the next paragraphs we will describe how the spectrum management is done within NATO.

## 1.1 FREQUENCY MANAGEMENT IN NATO

In NATO one can distinguish three levels of spectrum management:

- The strategic level, for homeland or national spectrum management.
- The operational level for spectrum management in the operational theatre.
- The tactical level for allocating the frequencies within a spectrum band.

### 1.1.1 The strategic level

For the strategic spectrum management within NATO territory the principle is that the spectrum management is a national matter and the responsibility of the national regulator. However, NATO will try to harmonize the military frequency bands. For this, NATO has set up the "NATO Joint civil and military Frequency Agreement (NJFA)" document, containing frequency bands that need to be allocated for military systems. In this way, NATO can guarantee that military radio equipment can be deployed throughout the whole NATO territory. If a country wants to join NATO, it has to ratify this document.

Within NATO Europe, member nations have delegated the control of certain frequencies and frequency bands to NATO itself. These frequency bands are:

- the HF Land pool (see FM handbook).
- the NATO UHF band (225 – 400 MHz).
- the VHF Off-route pool.

For this, the NATO C3 Board has the Frequency Management Sub Committee (FMSC), which is responsible for the daily management of these frequency bands. Note that what is presented here reflects the former NATO Board structure. This structure was changed in 2011.

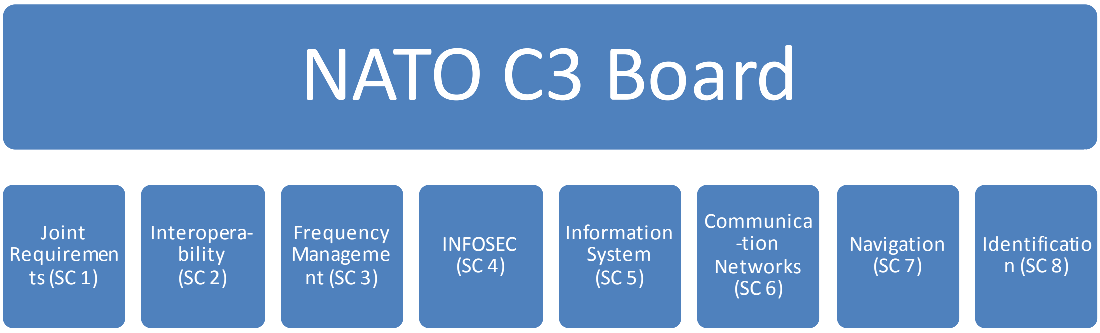


**Figure 1-2: NATO C3 Board Structure.**

Each NATO member also has on the national level a "National Allied Radio Frequency Agency" (NARFA) that will act as the single interface for frequency and spectrum co-ordination and management issues between the FMSC and the nation. NARFA's coordinate with each other and of course with the national regulator.

For the frequency bands under the FMSC management, the member states will jointly decide on the usage (type of application) of each sub-band. These decisions are made by the Spectrum Management Board (SMB). As an example, we list the spectrum allocation for the harmonized UHF band.

- Air/Ground/Air: 33 %
- Wideband Mobile (Tactical Radio Relay and other wideband applications): 25.8 %
- Satellite (GE, IT, SP, UK, US, NATO. FR and TU): 9.6 %
- Civil (Terrestrial Digital Audio broadcasting (T-DAB) and Digital Private Mobile Radio (DPMR) for Emergency Services): 8.7 %
- Navy series: 6.7 %
- ILS (Civil - Instrument Landing System): 3.9 %
- Miscellaneous (Airborne Early Warning (AEW), Military DPMR, Have Quick training, SATURN training, etc.): 12.3%

The tools that the FMSC has at its disposal to manage and allocate the frequencies are quite limited and static. Summarized they are composed of a database, a data exchange format (SMADEF) for all spectrum-related information exchange and a user-interface (ARCADE). Normally, the frequency allocation is done without frequency engineering tools. Only for a limited set of frequency band, the FMSC uses tools with calculation capabilities.

### 1.1.2 The Operational Level

At the operational level, the spectrum management is described in the reference document "ACP 190 NATO SUPP-1(C): NATO Guide to Spectrum Management in Military Operations". The principle is the following. At NATO-HQ a military Spectrum/Frequency Management element, called Theatre Frequency Management Cell (TFMC) will be assigned. The TFMC is responsible for liaison, negotiation, coordination, assignment and management of frequencies in collaboration with the Host Nation (HN) in theatre.

In international missions within NATO territory, the frequency bands are already harmonized, which will give the benefit, that military radio equipment can be deployed through NATO territory.

In international missions outside NATO territory, the use of frequency has to be established for a specific case. The local use of the spectrum and the role of the nation frequency management authority are important factors in the process. There are two main options: in case there is a national regulator, the spectrum allocation is provided by the regulator to the TFMC; and in case there is no national regulator, the TFMC is responsible for the spectrum allocation and for the management of the frequencies. The main role of TFMC is to perform the coordination of the frequency management and assignment for the coalition forces.

In NATO-led operations, there is not a specific procedure for obtaining frequencies. Normally, the Spectrum Manager, who deploys first, establishes a personal contact to the Ministry of Communications or a comparable Telecommunication Regulatory Authority to negotiate and tries to obtain sufficient frequencies or even bands for the deploying units to fulfil the NATO-led mission. In general, this will be fixed on paper (e.g. a Memorandum of Agreement).

The tool that the TFMC normally uses to manage the frequency allocation is "SPECTRUM XXI" (SXXI). SXXI is owned by USA, but provided to NATO for NATO-led operations only. SXXI has the following capabilities: it can do Frequency Assignment, Interference Analysis, and Equipment Certification. It has also Frequency Engineering capabilities and some Electronic Warfare (EW) Support.

### 1.1.3 The International Security Assistance Force (ISAF) case study

The frequency management at ISAF is based on a Memorandum of Agreement (MOA) between ISAF and the Afghan Ministry of Communication and Information Technology. The MOA has to guarantee the efficient use of the electromagnetic radio frequency spectrum by ISAF units and to define the specific policies and procedures for the coordination of frequencies by the parties. The structure for the frequency management is depicted in Figure 3. It can be seen that the structure is complex and includes many different actors. Central in the structure is the ISAF HQ with the TFMC. The TFMC has to coordinate with many other actors like the host nation, the regional commands with the units from different member states, but also with the non-governmental organizations (NGOs) and the National Allied Radio Frequency Agencies (NARFAs).

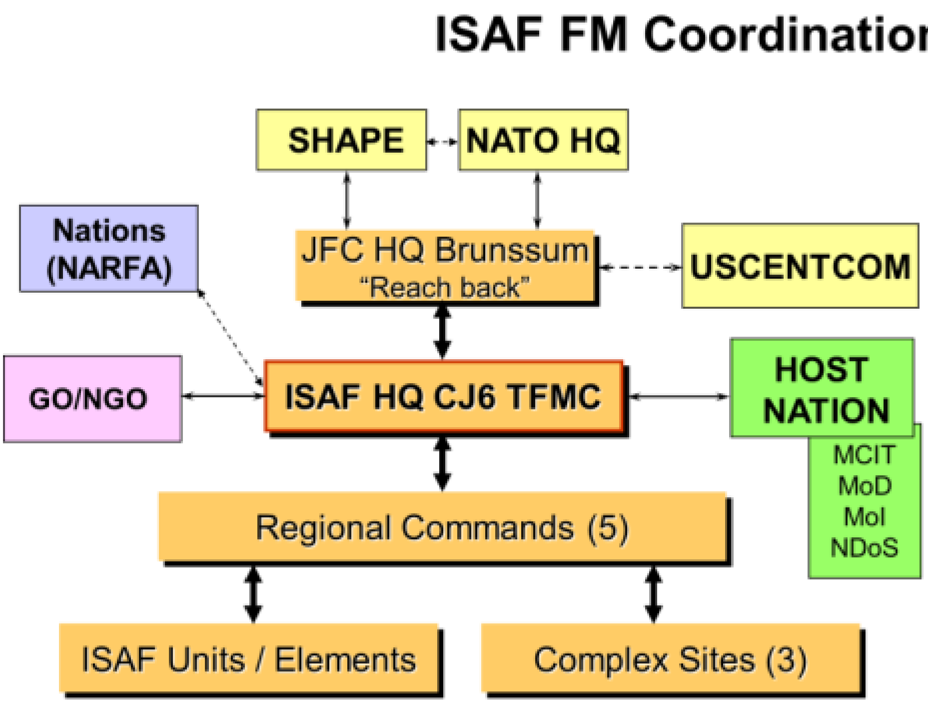


**Figure 1-3: ISAF Frequency Management Structure.**

In such a complex environment one could expect a lot of interference. Unfortunately, not a lot of data is available on interference problems in Afghanistan. This is mainly due to the fact that Interference reports are not filled in by the users. The main sources of interference could, however, be identified as:

- Own Troops Communications:
  - Unauthorized frequencies.
  - ECM: unintentionally / deliberately.
  - Hardware failure.
- Minister of Communication and Information Technology Customers:
  - Unintentionally / deliberately.
- Unknown Source / "Enemy".

During the ISAF operation, some critical issues could also be identified

- There is a significant increase of interferences - units using unauthorized frequencies ("own" frequencies).
- There is a lack of control on ISAF frequencies - lack of spectrum analysis and monitoring capabilities.
- Frequency bands heavily crowded (Kabul, Kandahar) - high concentration of ISAF forces.
- There is an increasing requirements in civil/shared bands - lack of coordination with ISAF CJ6 TFMC prior to deployments.

### 1.1.4 Conclusion on the NATO Spectrum Management Procedures

As a conclusion we can state that the spectrum management and the frequency allocation in NATO today are based on a fixed allocation (licensing). All member states try to harmonize the frequency bands for military use. Due to the many actors within NATO, the allocation is very static and it can take years to change the allocation of a frequency band.

Also in NATO operations outside the NATO territory, the spectrum and frequency management can be complex, especially in countries in which no national regulator is available.

Further, it can be noted the tools for strategic and operational frequency management are also limited and often don't include frequency engineering capabilities. As a consequence, a lot of frequencies cannot be reused elsewhere (based on space division multiplexing).

It can be expected that with the increase of military communication systems demands and the limitation of the spectrum resources for military use, it will inevitably lead to spectrum scarcity due to the inefficiency use of the spectral resources. Hence here is a need to establish a smarter and more flexible use of the available spectrum.

## 1.2 EXPECTED BENEFITS OF COGNITIVE RADIO FOR NATO

With reference to the identified deployment problems using static frequency planning, it is clear that situation-aware spectrum use, such as that enabled through Cognitive Radio (CR) and Coordinated Dynamic Spectrum Access (CDSA), will have a significant potential to solve these identified problems or at least to improve the situation. We will here review typical cases in which CR and CDSA will be of particular benefit:

- Improved spectrum utilization in a densely populated theatre.

As described above, in a densely populated theatre there is an increasing risk that static frequency assignments will fail due to some uncoordinated coalition radio system in the theatre or due to unforeseen interference. In such conditions, CR and CDSA systems will be able to dynamically adapt to the situation encountered. In densely populated cases, in which there is a high demand for communication capacity in a particular region, CR and CDSA will enable improved utilization of the spectrum in the region, and a resulting higher communication capacity than in the static planning case. The improved utilization will be achieved through exploitation of "holes" in frequency spectrum and time, and through exploitation of patterns of variable spectrum demand over time between systems.

- Scenarios with a high degree of dynamics.

Such dynamics may be rapid geographical movement of units, units entering and leaving the scenario or varying communication needs. A node or network in a CDSA system will request a new frequency lease if the old lease expires due to the geographical movement. It will also request a new lease if its communication links provide inadequate communication capacity, or release its lease and obtain a new reduced lease if its operational communication capacity requirements have been diminished. Similarly, units entering a scenario will obtain new leases and units leaving the operation will release their leases.

Networks of CR nodes in the same way will adapt to the dynamics by making new decisions of their use of spectrum, and exploit opportunities in accordance with their policies.

- Scenarios with a-priori unknown sources of interference.

As reviewed, with static frequency planning there is a risk that the pre-planned frequency assignments are unusable due to electromagnetic sources in the theatre that were not accounted for in the planning process. With CDSA, the CDSA functionality after some time will have an updated view on the interference situation, and the leases it provides to the radio nodes will have taken this into account. CR networks similarly will sense the interference and avoid the problematic parts of the spectrum when making spectrum decisions.

- Scenarios in which the interference varies in amplitude and frequency over time.

CR networks will have continuous monitoring of the spectrum and attempt to make optimal spectrum use decision based on the observations. In the same way, the CDSA functionality will monitor the spectrum through monitoring stations and through sensing capable radio nodes, and issue new leases when needed.

In both cases, due to control loop delays, and being more pronounced in the CDSA case, fast varying interference will be difficult to handle through blindly reacting to sensing feedback only, more advanced analysis of interference patterns or counteraction through waveform adaptation in the direction of more robust ECCM waveforms are types of actions that will be needed in such cases.

Additionally, both CR and CDSA systems may provide a greatly improved spectrum situational awareness: CDSA systems, through the combination of the granted frequency leases and the knowledge obtained via its spectrum monitoring stations and sensing capable nodes, may provide a unified view of the electromagnetic activity in the area of operation. This view may be used as input for the intelligence gathering of the progress of the operation, for planning EW actions, and as input for the battle management. Coordinated CR networks may provide such a view on a more local scale, but in this case it will be more difficult to distinguish between the coalition's use of spectrum and other radiation sources.

## 1.3 REPORT OVERVIEW

The RTG-035 group "Cognitive Radio in NATO" is the first initiative about the use of cognitive radio in NATO. The group was set for three years, from 01/2007 to 12/2010 and was then extended to 12/2011. The Technical Activity Proposal set in 2007 was listing the different work items which were taken as a first program of work:

- To make a review and synthesis of the cognitive radio technologies explored within NATO countries in the military field.
- To make a review of civilian technologies available for military cognitive radio now and at mid long term.
- Investigate the techniques and technologies which could implemented at mid long term in a cognitive radio and provide a technology roadmap planning.
- To analyze the benefit of cognitive radios integration in NNEC NII architecture.
- Propose to the NATO community relevant axis of works on cognitive radios.

Most of the items have been covered and results are captured in this document. The work has been refined along the duration of the group. The group focused on the use of cognitive radio for improving the efficiency usage of the spectrum in the context of coalition operations as explained in Section 1.2. Chapters 2 and 3 present possible applications of the CR within the context of in Network Centric Operations. Chapter 4 presents the adaptive capabilities of the wireless networks and the corresponding challenges for CR and Chapter 5 discusses the needs for dynamic adaptations. Chapter 6 deals with the use of EW in the context of CR. Chapter 7 is dedicated to various technical solutions that may be used in the context of CRs, such as iterative water filling, game theory, architecture and protocols.  Chapter 8 depicts the first results about a "coarse-grained" simulation methodology that could be used by all to compare and assess performance of CR solutions in a fair way. Chapter 9 proposes how to depict the scenarios and vignettes to feed the simulations presented in Chapter 8. The document ends with conclusions and recommendations in Chapter 10.

## 1.4 REFERENCES

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# Chapter 2 – COGNITIVE RADIO IN NETWORK CENTRIC OPERATIONS

## 2.1 CHARACTERIZATION OF THE ELECTROMAGNETIC ENVIRONMENT AND SPECTRUM REQUIREMENTS IN NETWORK CENTRIC OPERATIONS

Network-Centric Operations (NCO) seek to translate an information advantage into a combat power advantage, through a robust network-linking of friendly forces [1]. The four basic tenets of NCO, which well convey the core of its foundational hypothesis, are [1]:

- A robustly networked force improves information sharing.
- Information sharing enhances the quality of information and shared situational awareness.
- Shared situational awareness enables collaboration and self-synchronization, and enhances sustainability and speed of command.
- These, in turn, dramatically increase mission effectiveness.

Although the referred-to networking aspects also have human and organizational dimensions, NCO fundamentally depends on efficient and robust data networking. The robustness requirement implies that the data connectivity needs to be reliable over time, geographical location, organizational regrouping and when subject to fierce electromagnetic conditions. Further, the shared situational awareness, even when employing state-of-the art data compression and distributed storage, requires an increase in data communication capacity, requiring wider-band more spectrum-demanding waveforms. The co-mingling of all air-, sea- and land-forces implies a complex web of communications systems that all need to cooperate in the geographical area of the specific military operation. Implicit in NCO there is also a higher degree of dynamics in operations, implying that data communications will need to rapidly adapt to new scenarios, locations and needs.

Mobile Ad Hoc Networks (MANETs) have become the basis for the communication networks in NCO [2]. Narrowband MANET systems have existed for many years, yet their data rate of a few kbit/sec is very limited relative to the needs of NCO. The MANET systems typically proposed for NCO operations are wideband networking systems. As an example, the DARPA Network Centric Radio System (NCRS) uses from one to six 1.2 MHz frequency segments [3].

With multiple MANETs deployed in an area of operation, as well as soldier radio systems and the multiple radio-links between different forces, it is clear that the requirements for spectrum can be very high in the specific area of operation. In particular if the topography of the terrain is such that the MANETs will need to run in the upper VHF or lower UHF range, very dense spectrum usage may result, requiring efficient exploitation of the available spectrum.

We also need to assume that civilian systems are operational and consume spectrum in the same area of operation. Additionally in a military scenario there is a high probability that there are sources of electromagnetic emission that were not accounted for in the mission preplanning process, ranging from imperfect pre-knowledge of the regulations in the area of operation, through exploitation of the spectrum by anarchistic elements in the area, and to spectrum use by unfriendly parties. This use of spectrum may be static, dynamic in frequency and/or time, or stochastic in nature. In particular this use of spectrum may be due to cognitive radio equipment with unknown policies and capabilities.

We also need to take into account the probability of malicious elements in the form of Electronic Warfare (EW) activities. While EW traditionally is operated separately from the communication equipment, the deployment of SDR technology in military environments enables such EW functionality to be highly distributed and integrated with communication equipment. It also allows EW to be highly adaptive and target specific weaknesses in the communication waveforms used in the area.

There is a high probability that forces within a nation are coordinated on their use of frequencies in the area of operation. Whether all coalition parties participating in the NCO are coordinated is an uncertainty.

We will use the mentioned characteristics of the anticipated spectral environment as a basis for the discussion of cognitive radio and CDSA in the following.

## 2.2 COGNITIVE RADIO IN NETWORK CENTRIC OPERATIONS, BENEFITS AND RISKS

As presented in the previous section, the spectral environment in Network Centric Operations may be demanding and complex. We will review how CR may be of benefit in such an environment, but also point out risks and challenges.

We will use the term Cognitive Radio (CR) in its broad interpretation *a context-sensitive radio that may use its accumulated context-knowledge to reconfigure its functionality, including its receiver and transmitter parameters, and that has the ability to learn from the effects of its reconfiguration*.

We will assume that the CRs cooperate within groups of CR nodes that aim to communicate using the same spectral resource. The typical assumption of some kind of control channel between the nodes for the administrative traffic in their coordination of the use of spectrum is assumed. Approaches with negotiation and coordination between such groups of nodes on the sharing of spectrum resources will be dealt with in 2.3.

### 2.2.1 Dynamic Spectrum Access

We have seen in the previous chapter how legacy frequency planning has many shortcomings in light of experiences from recent operations. In an anticipated NCO spectral environment, this type of frequency planning will in particular have problems in dealing with the dynamics of the operation, for example a rapid movement of forces that was unforeseen in the preplanning process. Also, the many unaccounted-for emitters in the area of operation are likely to cause degraded communication links. While static and quasi-static such emitters may be taken into account in a revised frequency plan for the area, the dynamic, stochastic and malicious emitters will be difficult to handle adequately due to the long lead time of the planning process relative to the dynamics of the emitter changes.

In contrast, CRs make dynamic and distributed decisions on spectrum use, and hence will enable spectrum usage that adapts to the spectrum usage at the particular location of the operation. In the following we will make the assumption that all the coalition nodes in the operation are CR nodes, and discuss the ability of CR nodes in handling the various sources of interference listed in Section 2.1.

**Regulated Users and Static Interference**

Avoiding regulated users and static interference is an issue that is very similar to the ‘primary user versus secondary user’ scenario which is dealt with extensively in the CR literature. Radio links with CR-enabled transmitters and receivers, and networks of CR transceivers, will through their sensing and spectrum decision functionality readily avoid any static interference, such as broadcasters. Regulated spectrum may be masked off totally by policy rules in the CR, or avoided on a dynamic basis with some minimal interference to regulated users. Policies may also, if required in the operation, be set to use the regulated spectrum in an interfering way if necessary.

As also described extensively in the literature, interference may be caused to nodes that are undetected by the CR.

**Optimum DSA Between (CR) Coalition Systems**

Spectrum assignment between groups of CR nodes that share spectrum may be viewed as a game between players. The challenge in this case is that the optimality criterions for each (player) should take into account some desired performance state of the total system (or system of systems). As an example, if some nodes are too greedy they may claim and use unreasonable amounts of spectrum resources, this may cause resource starvation and too low bit rates with other nodes in the system.

**Coexistence with CR Systems with Unknown Policies**

The coexistence of CR systems with different and unknown policies will be an additional challenge. As an example, some systems may have greedier policies than others, leading to unfavourable rates for the less greedy ones. Other examples are systems with non-rational policies, and systems deliberately trying to cause resource starvation of others.

**Dynamic and Random Interference**

The ability of a CR to deal with dynamic and random interference depends on its sensing and learning abilities, and it will depend on its cognition cycle length. Any dynamic spectrum interference with durations typically much longer than the CRs sensing memory length and its cognition cycle, should of course be handled well. Fast varying dynamic and random interference will be challenging for the CR to handle. As an example, a sensing algorithm that does quasi-peak sensing over a spectrum interval over a time period, may due to dynamic and random interference mark large parts of spectrum as occupied, resulting in wrong spectrum decisions and less-than-optimum bit-rates.

**Malicious Emitters**

The cognition abilities for a CR to be used in a NCO scenario will need to take into account malicious emitters that deliberately want the CR to take wrong or suboptimal decisions. This will be discussed further in Section 2.2.2. and Section 2.2.3.

### 2.2.2 Waveform Adaptation

In addition to distributed dynamic spectrum allocation, the CR functionality enables each radio node to adapt its waveform to its actual context.

A spectrum decision, as viewed from one CR transmitter, in the general case will be in the form of a spectral power density S(f) over some spectrum region B. The CR may additionally decide how to best utilize this resource, for example which modulation(s) and coding(s) that should be used. Important metrics in making this decision is the signal-to-noise and interference (SNI(f)), at the corresponding receiver, over B.

Other important metrics in making the waveform decisions are the hostility of the environment, the channel reliability required and communication bit rate required. Highly hostile electromagnetic environments may dictate trading off capacity for reliable connectivity at lower bit rates.

Such hostility concerns may also influence on the spectrum decisions themselves, causing the CR, for example, to use a lower S(f) over a wider region B than would otherwise have been used, or causing it to vary S(f) according to some quasi-random pattern.

Waveform adaptation will also be vital in ensuring interoperability between communication equipment.

### 2.2.3 Integration of Communication and EW Functionality

**Operational Aspects**

In NATO terms the electromagnetic environment is considered an operational environment equivalent to air, sea and land. The success of military operations is heavily depending on the ability to make effective use of the electromagnetic spectrum and at the same time controlling or exploiting the opponents' use of the electromagnetic domain. A main part of military command, control and information systems is based on various types of wireless radio systems. In addition an important part of military intelligence, surveillance and reconnaissance, are extracted from electromagnetic signals.

Even if cognitive radio systems are intended to provide an improved utilisation of the radio frequency spectrum they do also inherently have a number of features that directly address military applications:

- Characterisation of the radio environment will contribute to establishing "situation awareness" in general using Electronic Surveillance Measures (ESM).
- The ability to avoid interference may assist own communication resources to cope with adversary jamming (Electronic Defence).
- The radios transmit chain may in principle be used as a source for generation of interfering or deception type of signals (Electronic Countermeasure - ECM).

Cognitive radios rely on the capability to scan for active radio signals. This data is used for coordinating the communication systems. Provided that the data is captured in near real-time this kind of information will also support formation of the situation picture or Electronic Order of Battle (EOB). This function is very similar to part of the functionality of COM-ESM sensors included in modern EW-systems. Dedicated ESM-sensors will most likely have superior performance with respect to the scan-speed and sensitivity offered by cognitive radios, but the concept of including ESM sensor capability in a communication network node opens new possibilities for connecting the sensors together in a sensor network.

**Networking of COM-ESM Sensors**

Networking of COM-ESM sensors is not a new concept. The main benefit is that combining the available spectral information from multiple nodes enables a more precise surveillance picture to be elaborated using, for example, direction finders obtaining a transmitter location. In a military cognitive radio system, both the sensor and the communication networks share physical platforms. This will make it feasible to design an integrated system in which the sensor and communication modules are transmitted over the same physical channel. The resource management and mechanisms for assigning of capacity according to service level agreements and policies will be needed.

**Multifunctional RF Units**

Looking at the receive part of a cognitive radio as a COM-ESM sensor is the first evolutionary step toward a situation in which a complete radio unit may be used for different applications depending on the current user requirements. The natural next step is to exploit the transmit parts of the radio in a COM-ECM role. In such a scenario the radio is truly a multi-function RF unit, potentially capable of communications as well as various types of Electronic Warfare. Whether it is advantageous to use the radio in a traditional jamming-mode needs to be further clarified, but as the transmit stage will incorporate a modulator (most likely to be implemented in software) the radio will in principle be capable of generating a variety of different waveforms. The most realistic scenario may be to use this capability for generation of deception type of signals, which are waveforms that imitate the real communication signals used by the opponent forces. Principally, the radio's transmit stage can also be used for conventional jamming purposes in which a strong noise or interference signal is used to block enemy communications. However, due to power-limitations, this is hardly realistic unless the target system is very close to the radio unit.

### 2.2.4 Summary of Benefits, Challenges and Risks for CR in NCO

Benefits:

| |
|---|
| Allows dynamic, operation-adapted spectrum assignment to take place. Does not depend on the accuracy of frequency planning relative to actual frequency deployment. |
| Handles very well static and slow dynamic interference sources in the theatre of operation. |
| Networks of CRs may obtain a unified view of ESM in its area of operation. |
| A network of CRs may use its accumulated information on its own communication needs together with its unified ESM view to synthesize intelligent EW. |

Challenges and risks:

| |
|---|
| Risk of disturbing undetected receivers. |
| Risk of short-time interfering with telecommunications infrastructure. |
| Optimum spectrum resource sharing between different coalition CR networks. |
| Optimum spectrum resource sharing requires knowledge of the achievable bit rate region for each CR link. Setting bit rate targets too high may lead to starvation of other CR links. Calculating the achievable bit rate regions requires global knowledge, and is very computationally demanding. |
| Spectrum resource assignment when there are CR networks with unknown or non-rational spectrum allocation policies, 'clever' opponents or negatively-behaving opponents. |
| Fast dynamic varying interference, and random interference. |
| Handling of malicious emitters / EW. |
| Vulnerability of CR coordination channels. |

## 2.3 CDSA IN NETWORK CENTRIC OPERATIONS

We use the term Coordinated Dynamic Spectrum Access (CDSA) to mean a functionality that enables coordinated distribution of dynamic spectrum in accordance with a defined measure of goodness for the system of all radio nodes. This functionality may be a central spectrum broker, a hierarchy of spectrum brokers, fully distributed broker functionality or any other implementation of inter-group coordination that performs the equivalent function for the system (or a regional part of a system). Since a discussion involving all the different CDSA architectures and implementations may become lengthy, CDSA will here be viewed from a conceptual viewpoint as an idealized spectrum broker or coordination entity (CE). The CE has the global knowledge and decision power on all use of spectrum. In the discussion we make a general assumption that there is a way for the individual nodes to communicate with this broker functionality, in the form of a basic data connection or some kind of specific control channels from the nodes into an internet and thus to the broker.

### 2.3.1 Dynamic Spectrum Assignments through CDSA

With the CDSA approach, each radio link, or group of radios that are to communicate, sends requests to the CE for a spectrum lease. We define a spectrum lease as a tuple $\psi$={F,T,P,A}, where F is spectrum interval, T is the time interval, P is the power or alternatively power density, and A is a geographical area. If granted, the lease provides the right to use the resource defined by $\psi$.
The CE will accumulate all knowledge concerning the use of the spectrum resources, such that it always will have an updated view. CE will grant or reject leases depending on the availability of resources as a function of this updated view.

A fully optimum distribution of the spectrum, in accordance with some global optimization criterion, such as the sum capacity for all nodes, requires that the optimum distribution of leases is calculated for each new lease request. Such exact global optimum solutions will, however, be intractable when the number of radio units is high. The use of genetic algorithms has been suggested as a way of finding quasi-optimum solutions to spectrum power density distribution between nodes, yet still the complexity and required computing time is likely to be high. Additionally, a redistribution of leases following such a recalculation will require considerable communication capacity.

As a more practical approach, time-limited leases may be granted on a first-come first-serve basis. *A priori*, the CE would have estimates of the number of links or networks required, and of the available spectrum resources, such that the leases can be granted with fairness relative to these estimates. In the unlikely event that available spectrum resources are exhausted when a new request arrives, previously granted leases will then be recalled or modified to allow the new spectrum lease. The capacity of leases can also prioritized by the CE, according to the priorities assigned to each originator. As lease renewals are iterated over time, the CE may re-evaluate individual needs relative to global needs and in this way the leases will iterate toward fairness and in accordance with the CE’s optimization parameters.

Next, the CDSA approach will be qualitatively analyzed relative to the same electromagnetic environmental influences as in the CR case.

**Regulated users and static interference**

All regulated spectrum use in the field of operation may be pre-entered in the CE's database. In the case of a policy to avoid the use of these spectrum intervals, they can thus be readily avoided.

Other, *a priori* unknown, static interference will initially be unknown for the CE. The CE may, however, have monitoring stations, and may receive sensed spectrum data from CR-enabled radio nodes, to complete its view of spectrum occupancy. In this way it will over time build up a knowledge concerning the actual spectrum use, such that the static spectrum interference can be avoided.

**Optimum DSA between coalition systems**

It is assumed that all coalition systems agree on the format with which to send and receive spectrum requests and spectrum leases to/from the CE. As an example, SMADEF [4] has been worked out by NATO as a format for interchanging frequency planning information. When all systems adhere to the policy of asking for spectrum leases prior to starting transmission, the systems will be guaranteed coexistence. The total amount of available spectrum resources in a region may, however, limit the bit rate of each system to a lesser value than its target rate.

**Coexistence with systems with unknown policies**

Communication systems not adhering to the spectrum lease policy for whatever reason will need to be treated by the CE as interference. The CE will gather information on the occupancy of this part of the spectrum, through its monitoring stations and through the individual CR nodes, and will take this interference into consideration when granting leases.

**Dynamic and Random Interference**

The CE will continuously try to keep an updated view on the interference in the region, comparing observations from monitor stations and CRs to the actual spectrum leases that have been provided. However, both the spectrum sensing and the communication of these spectrum readings to the CE will have certain lead times, and hence there will be a delay before the source of interference has been actually recorded in the CE's database. Probably this delay will be on the order of fractions of a minute to more than one minute. It will hence be difficult to keep an updated view on sources that have a random use of frequency, or that quickly change operating frequency.

Based on its observations of the interference, the CE may re-assess the optimum shape of the leases it provides, i.e. high power density narrow-band versus low-power-density wide-band.

**Malicious Emitters**

See 2.2.1.

### 2.3.2 Waveform Adaptations with CDSA

The CE will provide the spectrum lease in the form of the tuple $\psi$, but it will not dictate specific waveforms in the radio nodes. The group of radio nodes that has received a spectrum lease will autonomously determine how to best utilize it.

The modulation and coding selected by the group of radio nodes will be both dependent on the type of spectrum license provided and also take into account the local interference situation and the hostility of the electromagnetic environment.

### 2.3.3 Integration of Communication and EW in CDSA

**Electronic Surveillance: The Integrated View**

The CE may systematically gather information on electromagnetic emitters, their location, radiation and other characteristics. Both special monitoring stations, as well as other sensing-capable transceivers may be utilized in this information gathering. Since the CE has a complete view of all legal and friendly-force spectrum leases, it may compare this information with its gathered interference. This will allow a higher level of electromagnetic situation awareness, with an integrated view of the electromagnetic emitters within an area.

**Electronic Defence: Assist Radio Nodes**

The CE's ability to avoid spectrum with high interference when granting leases may assist its own communication nodes in dealing with jamming. Static and slow dynamic interference or malicious emitters may be handled in this way.

The CE may also assist the decisions at the radio nodes by virtue of the types of spectrum leases it grants, depending on the type of interference scenarios it observes. Examples of situation-dependent leases are a lease with low power density but over a wide frequency interval, narrow-band with high power density or a discontinuous spectrum.

Note that while the CE assists the radio nodes in this manner, electronic defence actions will still heavily depend on autonomous decisions within the communicating group of nodes.

**Electronic Offensive Actions: Coordinated Action**

With radio nodes being CRs based on SDR platforms, in addition to their communication purposes these may also be used as versatile, intelligent offensive emitters. In principle the radios can be used as traditional noise jammers to block adversary communications. However, such broad jamming may also interfere with own communications and should be avoided. A more innovative solution is to utilize the transmission capabilities as part of a coordinated deception plan. Such coordinated offensive action involving a high number of radio nodes, transmitting normal communication type of signals, may be orchestrated from the CE.

### 2.3.4 CDSA Coordination Channels

The effectiveness of CDSA functionality depends heavily on the reliability of the data channels used for the coordinating communication, between CDSA entities like a CE and the radio nodes, and between different CDSA entities. Many publications refer to fixed control channels for this purpose. Such control channels may map into a fixed wirebound data network where possible.

In NCO environments, there will be even higher reliability requirements on this administrative communication. Additionally, there will be demanding security requirements, as we neither want spectrum lease information to come into unfriendly possession, neither do we want the possibility of having false leases injected into the system, possibly causing confusion and blocked communications. Hence, robust ECM, TRANSEC and COMSEC measures are needed for this administrative communication.

### 2.3.5 Summary of Benefits, Challenges and Risks for CDSA in NCO

Benefits:

| |
|---|
| Allows dynamic, operation-adapted spectrum assignment to take place. Does not depend on the accuracy of a-priori frequency planning relative to actual frequency deployment. |
| Handles static and slow dynamic interference sources very well in the theatre of operation. |
| Can handle capacity fairness and priority between different groups of radio nodes, through issuing leases. |
| Since the central CDSA entity, or some distributed CDSA entity, has global knowledge, it is possible to calculate possible regions of target capacity. |
| A central CDSA entity, or some distributed CDSA entity, may get a unified view of ESM in its area of operation. |
| A central CDSA entity, or some distributed CDSA entity, may use its accumulated information on all friendly communication together with its unified ESM view to synthesise intelligent EW. Such offensive actions may be carried out in a coordinated way using a high number of radio nodes. |

Challenges and risks:

| |
|---|
| Fairness between users can be temporarily violated when the coordinating entity runs out of spectrum, but fairness will be obtained through the revocation and renewal of leases. |
| Always trying to optimum spectrum assignments will be very computationally demanding, and is not recommended. |
| Estimating target bit rates and estimates for the required capacity in a region, will be computationally demanding tasks. |
| Fast dynamic varying interference, and random interference. |
| Handling of malicious emitters / EW. |
| Vulnerability of coordination channels. |
| Attacks on the CDSA functionality. |

## 2.4 SUMMARY: COMPARISON OF CDSA AND CR IN NCO

Both CDSA and CR will allow dynamic, operation-adapted spectrum assignment to take place. Both principles will easily handle static and slow-varying dynamic interference sources in the theatre of operation. CR nodes not relying on a distributed or central CDSA functionality may take faster decisions on frequency use and hence may cope with faster-varying interference, but such interference will still be a major challenge to handle and a risk for the system.

CDSA may ensure that communication rates are distributed in a fair and sensible way between users. With uncoordinated CR networks, there is a risk of certain nodes being too greedy, causing resource starvation at other nodes. Another risk is nodes with unknown, non-rational or negative policies.

CDSA enables a unified view of ESM in its area of operation. The accumulated view of the friendly communication together with its unified ESM view may be used to synthesize offensive EW actions in a coordinated way. Cooperating networks of CRs, which will tend to be a distributed CDSA, may also obtain a view of ESM in a local area.
In both cases, advanced decision algorithms and autonomous actions will be needed to handle malicious interference, not only relying on sensed feedback.

Frequency assignment through CDSA principles will be more computationally demanding than autonomous CR operation.

The coordination channels between CDSA entities and radio nodes will be vulnerable and must have ECCM protection. The same applies for the coordination channels within the CR networks.

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# Chapter 3 – NET ENABLE CAPABILITIES AND COGNITIVE RADIO

## 3.1 FOREWORD

Net Centric Warfare (NCW), Net Enable Capability (NEC) and Net Centric Operation (NCO) have been largely described and commented on during the last decade[1]. There is no need to highlight the main impact of the NATO NEC feasibility study on the current developments being conducted for NATO. However, time will be needed to transform military organizations and processes to comply with the full aim of NCW, NEC and NCO. The main reason is that the military transformation cannot be other than a progressive evolution of the current situation.

As a consequence, the ideas provided here regarding CR and NCO have to be taken as material to progressively improve the military operation.

## 3.2 NET CENTRICITY

The concept of net-centricity began in the 90s with Network Centric Warfare (NCW) as military response to the Information Age. Then Net Centric Operation (NCO[2]) was introduced to enlarge the concept to any type of operation. In both cases the operational activities take advantage of networking being telecommunication infrastructure and/or people in collaboration.

NCW being a subset of NCO, the rest of this document will only talk about NCO. Term Net Enable Capability (NEC) will also be used to refer to ability to activity introduced by the networking within NCW- or NCO-oriented operations.

## 3.3 COGNITIVE RADIO

Regarding the fact that RTO-IST077 objective is working on the cognitive radio, only a simple definition, from Wikipedia, is provided here in order to fix the hypothesis for the needs of this document:

**Cognitive radio** is a paradigm for wireless communication in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently avoiding interference with licensed or unlicensed users. This alteration of parameters is based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, user behaviour and network state.

## 3.4 MAIN CONCEPTS OF NCO

### 3.4.1 NCO Domains and Value Chain

Highlighted by the Net Centric Operation Industry Consortium (NCOIC)[3], the domains concerned by the NCO are:

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[1] References [1] and [2] provide the fundamentals of these concepts.

[2] A comprehensive study of Command and Control structures and processes for NCO has been done by Jay Bayne (See reference [3]).

[3] NCOIC Courses (See reference [4]).

- The social domain is where the force entities interact, exchange information, form awareness and understanding, and make collaborative decisions.
- The cognitive domain is where the perceptions awareness, understanding, decisions, beliefs, and values of the participants are located.
- The information domain is where information is created, manipulated, value-added, and shared. It can be considered as the "cyberspace" of the NCO.
- The physical domain is where the operations take place. It is also where the infrastructure that supports NCO exists.

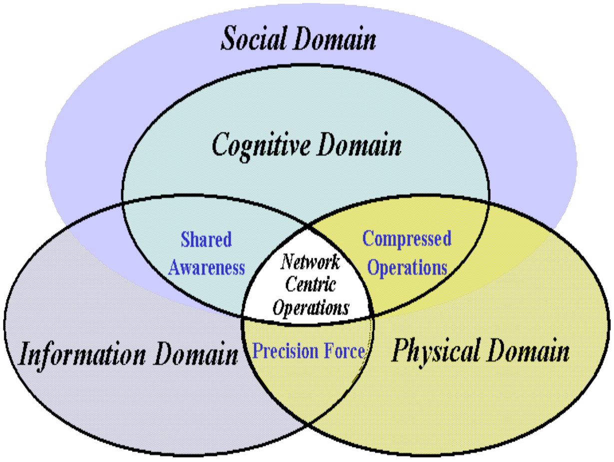


**Figure 3-1: NCO Domains (Source: NCOIC).**

NCOIC also summarized the main added-value introduced by the NCO in the military field as follow:

- Force is rapidly deployable, employable and sustainable; regardless of anti-access or areas denial environment.
- Force gains and maintains information superiority to shape the situation or react to the change.
- Force uses collaborative planning and share knowledge to empower subordinate commanders to compress decision cycles.
- Force has capability to have advantage over an adversary and/or his systems in all conditions and environments.

The NCO value chain presented by Figure 3-2 traces out the dependencies of the force, moving from the physical and information domains to the cognitive and social domains, and back to the physical domain. This process is actually very dynamic, and looks very simple, but its simplicity highlights the NCO challenges: how to translate an improvement in information sharing into shared situational awareness and mission effectiveness?

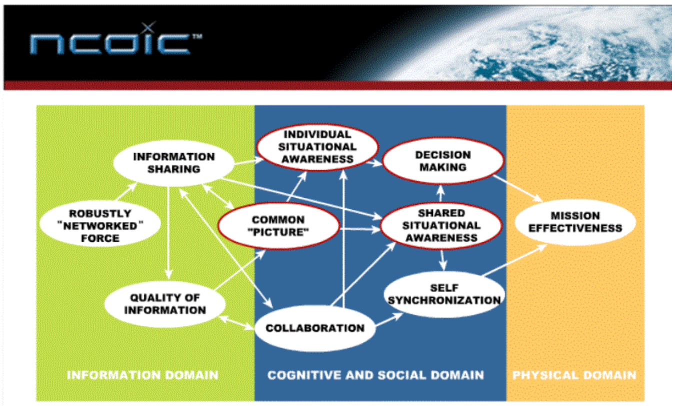


**Figure 3-2: NCO Value Chain (Source: NCOIC).**

### 3.4.2 Community of Interest

In the NCO concept, organisations and systems are networking in order to make their capabilities or information available and visible to others. Hence, a system including personnel may access via the network to get capability (represented as services) or information exposed by another system. This brings issues such as the right to use, the accessibility and the availability of services and information. In the context, the relationships between systems and organisations are generally organized into consistent collaborations or Communities of Interest (COI).

COIs are groups of entities (systems including personnel) having a common mission interest and information needs. During NCO, COIs are usually autonomous units inserted in an organization combining hierarchical command and cross-COI interactions. In such an organization, a COI is a unit of subsidiarity set up with a goal, with specific operational capabilities built from collaborating members (i.e. entities and/or sub-COIs), with an initial allocation of information and communication channels to support these collaborations.

The COIs may mix these different types: hierarchical or cooperative, and, ad-hoc or permanent. A system may belongs to several COIs. This implies that COIs are also networking in the NCO approach.

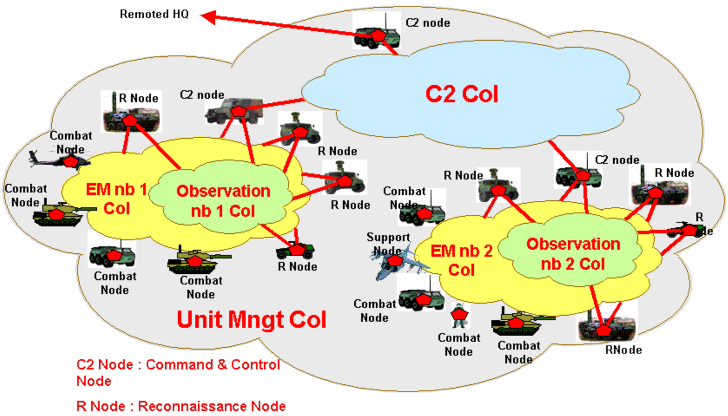


**Figure 3-3: Example of Land Ad-hoc COIs.**

## 3.5 LAYERS OF INTEROPERABILITY

### 3.5.1 Architectural Views

As defined by the architecture frameworks (e.g. NATO NAF) in order to master complexity, operation, systems and their interactions can be described in architecture views. Each view expresses a concern that a stakeholder (a part provider, a user, an acquirer, etc.) has on the system or the associated operations.

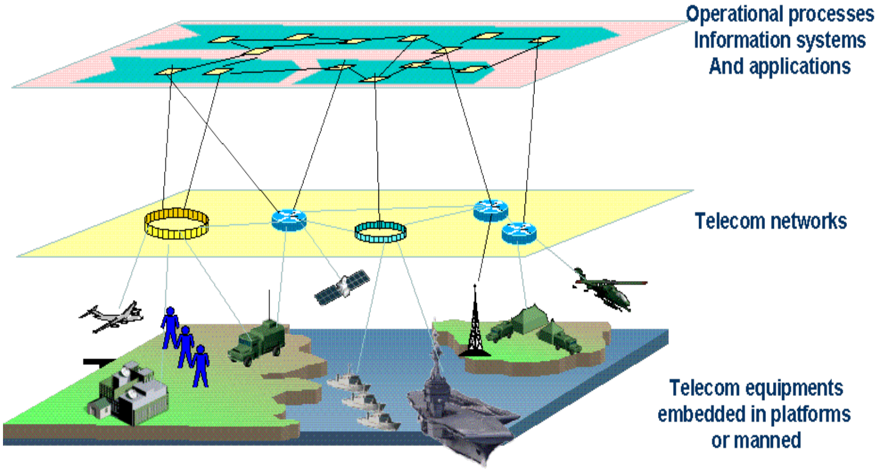


**Figure 3-4: Architecture Views.**

Regarding the objectives of the RTO-IST077 study, the architecture views can be considered:

- Operational view: describing the operational processes to fulfil the objectives (or the mission) with associated organization, activities, roles, and information systems.
- Optionally, the IT view: identifying separately from the operational in order to clarify the applicative architecture and constraints.
- Network view: describing the network topology, the protocols, the exchanges patterns (services, data, streams) and the associated quality of service.
- Equipment view: describing the telecom means, their characteristics and their environment (platforms, usage conditions, etc.).

### 3.5.2 Interoperability

Interoperability levels identified by NATO are:

- Operational: people and process.
- Procedural: information and services exchanges.
- Technical: network and transport.

These levels have been refined by several standardization bodies, for example the OMG and the NCOIC. The Figure 5 presents a summary of the layering considered by the NCOIC:

- NATO technical level includes levels:
  - From physical concerns with spectrum, waveform, propagation, signal processing, etc.
  - Toward network protocols for transmission, routing, etc.

- NATO procedural level comprises:
  - The IT exchanges (services, data, streams).
  - Their syntactical and semantic representation.
  - Their representation to the users according to their skills and knowledge.
- NATO operational level covers:
  - The proceeding of the interaction according to objectives, doctrines, habits, and operating modes and regulatory constraints (e.g. operational security policies).

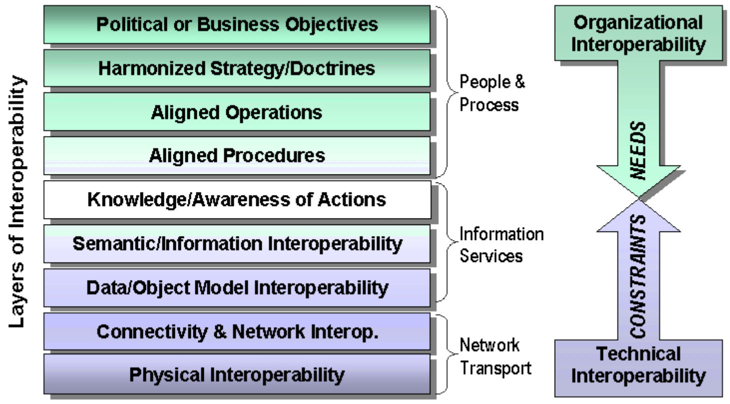


**Figure 3-5: Interoperability Levels (Source: NCOIC).**

### 3.5.3 Cross Layer Management

In order to efficiently support the operational command and control, and to conform with operational regulatory rules, transverse activities must be applied:

- For security:
  - issues are to maintain availability, integrity and confidentiality on the operations, and consequently on the systems, the equipment, and their interactions.
  - Security measures are applied on each architecture level for physical protection, secure transmission, secure protocol, labelling, authentication, authorization, etc.
- For management:
  - The issue is to adjust all capabilities according to the means (availability, quality of service) and the operational objectives.
  - Configuration, monitoring, supervision, and reconfiguration are implemented on each architecture level according to the needs.

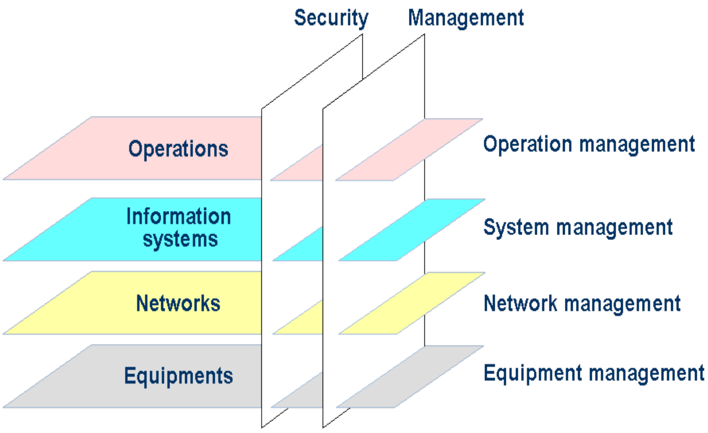


**Figure 3-6: Cross-Layers.**

In order to obtain a coherent behaviour of the different architecture levels, security and management must be organized as cross-layers activities. For example, a coherent and global functional behaviour is expected for security and management –but separately, for security reason.

### 3.5.4 Behavioral Patterns

In the past, research centred on C4ISR showed that military operations can be described with control-loop patterns. One of these is the Observe, Orient, Decide, Act (OODA) loop.

More recently it has been defined that Sense-Decide-Adapt (SDA) is a basic pattern to describe cognitive radio behaviour called "Cognitive Cycle" [5].

These two patterns are similar. The aim in both cases is to act according to the perception of the situation and reference knowledge to fulfil objectives.

The situation in this case can cover a lot of things but it at least should include the environment and the current status of the resource involved in the OODA or SDA loop (i.e. the observation/sensing activity get perception of the environment and the resource status). The action will adapt the resource status and behaviour, and will interact with the environment to make the situation evolving toward the expectation to fulfil the objectives.

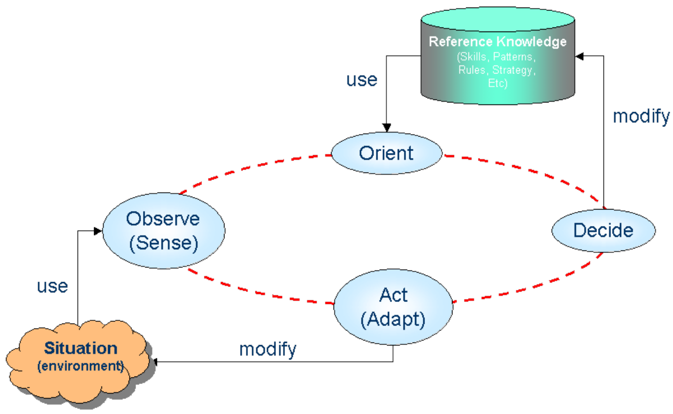


**Figure 3-7: OODA Pattern.**

As defined in the C4ISR concepts, the OODA loops are considered at each level of the military hierarchy and in each participant unit of a COI, This means that, from the strategic level down to the tactical level, the operational activity can be formalised with the OODA pattern, each level having its own reference knowledge and its own vision of the situation.

In a hierarchy and/or a COI, a military unit receives objectives/orders from the upper level of the hierarchy and demands from other units of the COI (as input of its OODA) based behaviour evolution and is able to send objectives to others according to the organisation rules and doctrines.

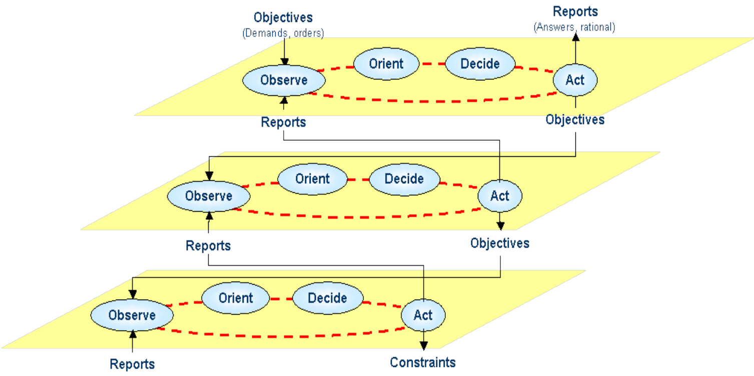


**Figure 3-8: Layering OODA Loops.**

In return each military unit provides feedback regarding the received objectives.

The OODA layering can also be considered to analyse the architecture views expressed in Section 3.5. OODA loops can be described at operational, system and tactical levels of the architecture. In this case, each term (objectives, situation, observe, orient, decide, act, etc.) has to be put in the architectural context.

For example, at the technical level of the architecture, the observation activity gets the perception of the technical and physical environment.

The system management, as transverse activity, insures that the OODA-based behaviours and objectives of the different units and architecture layers are compatible. Monitoring, supervision, and (re)configuration functions of the system management, as presented in Section 3.5.3, must be understood as transverse OODA loops.

## 3.6 NCO IMPACTS ON COGNITIVE RADIO

### 3.6.1 Behavioral Constraints of Equipment Embedding in a System

As long as cognitive radio is involved at the technical level of an architecture to sustain the system and operational activity, as explained in the previous sections, it receives objectives from these levels and reports to them. These objectives are:

- Functional objectives: the cognitive radio has to fulfil the different natures and patterns of system communication. For example:
  - For natures: video, image, data and services.
  - For patterns: send, receive, broadcast, multicast, publish and subscribe.
- Non-functional objectives. For example, ergonomics, reliability, performance and quality of service.

In a globally managed architecture, the cognitive radio must also be compatible with transverse system management, i.e. its embed radio management must be able to configure, monitor, supervise and reconfigure the radio functions. Further, as involved in a complete system and military hierarchy, it must be able to receive objectives (reconfiguration orders) and provide status (reports) of its activities.

### 3.6.2 Functional Benefits for the Cognitive Radio

As described in the Section 3.5.4, each entity of military unit and each architecture level can be seen as implementing an OODA loop. It can get a vision of the environment and influence it. All these perceptions and influences are to be combined coherently and efficiently.

From the cognitive radio point of view, many OODA operational loops and functionality can provide additional information to sense the environment and act accordingly. For example:

- A BFT (Blue Force Tracking) operational activity provides the location and the operational status of the friend force. Consequently, the BFT provides the location of the transmission means. This obviously helps to adapt the transmission signal (power, waveform, etc.).
- A SA (situation awareness) operational activity provides the positions, behaviours, and kinds of adversary forces. This includes knowledge of the electronic warfare assets detected by NCO means.
- A cartographic, weather and environment information are collected by NCO applications to provide command decision support. This information could also be used to optimise the radio signal propagation and signal processing.

### 3.6.3 Cognitive Radio Impacts on NCO

Cognitive radios involved in net centric operation can bring benefits in several ways:

- As sense-decide-adapt loop in implemented in the equipment. The radios can be considered as:
    - Sensors: they get an electromagnetic vision of the environment. This vision can consolidate the command situation awareness.
    - Effectors: they can interact dynamically with the environment. For example, the communication can be adapted to provide operational effects; they are no longer running only to fulfil the communication workload of the application.

For example, the radio can act as a jamming asset in addition to a transmission mean.

- As system management is fully implemented in the radio:
    - the sense information of the radio can be reported continuously the transmission status of the communication links to the situation awareness. The command force thus has real-time knowledge of its telecommunication networks.
    - The transverse system management decision can be applied at the radio level. This allows the dynamic adjustment of the radio behaviour to the operational demand. This is the only way to implement an efficient quality of service to support the applicative activities.

## 3.7 CONCLUSION

Network-Centric Operations, cognitive radio, and security and system management can, respectively, obtain benefits from one another.

As cognitive radio will certainly be involved in NCO, it is necessary to investigate in-depth the needs and the benefits of NCO for cognitive radio.

Considering that the radio is part of a fully layered architecture, it is also necessary to analyse the requirements of using radio with:

- Transverse security and system management.
- All system communication patterns and natures.
- Different kinds of system infrastructures (e.g. NATO NII).

Different other constraints have to be taken into account. Human Factors, logistics and life-cycle cost are now considered as major drivers for any military development, and can dramatically influence the system and equipment design.

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# Chapter 4 – ADAPTIVE WIRELESS NETWORKS

## 4.1 INTRODUCTION

A wireless network is a set of nodes that are interconnected to permit the exchange of information. From a network viewpoint, wireless networks are composed of links (logical or physical) and nodes (mobile or fixed). Nodes can be terminal or intermediate entities. Terminal nodes generate or use information transmitted over the network. Intermediate nodes transport the data information but do not generate or use the information. Links are used to move bits between nodes.

Wireless networks are highly dynamic systems because of the time-varying nature of links (quality, availability, etc.), nodes (mobility, density, energy, etc.), and data traffic (requirements, request patterns, etc.). Unfortunately, the dynamics in wireless networks can adversely affect the performance and service continuity. Consequently, network functions, adaptations, designs, and cognition are used or proposed to mitigate the effects.

In the next sections we present background material and discuss some research challenges related to adaptive wireless networks.

## 4.2 BACKGROUND MATERIAL

### 4.2.1 Network Functions

End-to-end information delivery is achieved by using a combination of various network functions. The main network functions include data transmission, medium access and scheduling, topology management and routing, error and rate (flow/congestion) control, and network security. Transmission functions are used to send data bits over a link. Medium access and scheduling functions coordinate the access and transmission of data in order to reduce the incidence of collision and efficiently use the broadcast network. Topology management functions establish and maintain physical or logical links and build a map of the connected topology with possible routes between nodes. Using the connected topology, routing functions find a desirable (best) path to transfer data from source node to destination node. Error control functions provide the ability to detect and/or correct information errors which may occur during transmission. Rate control functions regulate the rate of transmitting information across the network in order to prevent the receiving nodes (flow control) or the intermediate nodes (congestion control) from being overwhelmed by the sending nodes. Security functions provide access control (authorization) of the network resources and maintain the required integrity and confidentiality of the information transmitted, authenticity of the communicating nodes, and availability of the network.

### 4.2.2 Network Adaptation

Wireless networks are highly dynamic. This is mainly due to the time-varying nature of link quality and availability, node mobility, density, and power, and data traffic requirements and patterns. In order to catch up with the ever-changing wireless environment, network adaptation is required. In wireless networks, a node is composed of various components (like modulation schemes, ARQ protocols, TCP/IP protocols, etc.), which implement the network functions. Therefore, network adaptation can be achieved in two ways: reconfiguring the node components or the node architecture, i.e., physical configuration and functional organization of the node components.

- **Node components:** In this case, only the parameters of the node components are altered in response to changes in the network environment. For example, error and rate control protocols such as TCP can adapt to changes in network latency by appropriately adjusting the retransmission timeout time. In addition, TCP can control the rate of sending packets in response to network congestion by changing the congestion window size.

- **Node architecture:** In this case, node components can be added, omitted, or replaced by other components, which perform similar functions, in order to adapt to a new environment. Examples for this case include reconfiguring mobile nodes from using IP routing protocol to OLSR routing protocol and reconfiguring network of mobile nodes from independent (ad hoc) mode using 802.11 standards to infrastructure (hub) mode using 802.16 standards.

Note that adaptation can improve network performance in many ways including load balancing, reducing latency, and increasing efficiency, capacity, connectivity, and reliability. But on the other hand, poor adaptation can lead to oscillations and instabilities, high overheads and inefficiencies, and increased complexity.

### 4.2.3 Design Methodologies

Layered protocol architecture is one of the early design methodologies used in communication networks [1]. In a strict layered design approach, a group of related functions or protocols, which perform particular tasks, are organized in layers and a complete network is engineered by stacking all the layers together. Each layer provides a service to the layer above through an interface defined between the layers. Layers are independent from each other and interlayer communication is restricted to adjacent layers. A layered design has been widely applied in wire-line networks; OSI model and TCP/IP model are familiar examples of layered design approach. The layered design has a number of architectural benefits including:

1) simplification of design, implementation, and testing;
2) provision of flexibility in modifying protocols and services; and
3) promotion of interoperability and compatibility.

However, in a wireless environment this approach can become very inefficient and ineffective. Cross-layer design violates the layered design methodology by allowing non-adjacent layers to have direct interactions. This permits the joint design of network functions in multiple layers. Cross-layer design can improve the Quality of Service (QoS) performance by efficiently enabling protocols to continuously adapt to change in the environment. The disadvantage of cross-layer design is that the implementation of poorly designed cross-layer interaction can result in “spaghetti-code”, which will be hard to maintain. A highly coupled design can lead to inflexibility that may potentially hinder future innovations.

### 4.2.4 Network Cognition

The increasing demand for versatile services coupled with the inefficient use of limited wireless resources have led to the proposed introduction of cognition in wireless networks. There are different meanings of the term cognition, even within the communications R&D community. The term “cognitive network” has been extensively used in the field of communications and networking with many intended meanings. In this report, we refer to network cognition as the ability of the network to sense the environment and its context, learn, reason, and change its internal parameters in order adapt to a particular environment or context. A network with cognitive capabilities as a whole is referred to as a Cognitive Network (CN) [3]. This implies that a CN can perceive network conditions, learn and build a body of knowledge, and reason and adapt radio and network parameters in order to meet network performance requirements and efficiently utilize network resources, such as spectrum, power, and buffers, with minimum overhead costs. The primary focus of a CN is to meet end-to-end goals. The introduction of cognitive capabilities in communication networks holds the potential of improving network performance and solving network problems unforeseen in the design stage. The CN concept has many applications in wireless communications including spectrum access and sharing, network resources allocation, prioritization of tasks, and network security [4]. For example, a CN could be built with the ability to analyze its behaviors and identify security threats and neutralize them.

## 4.3 RESEARCH CHALLENGES

### 4.3.1 Dynamic Spectrum Access

Dynamic Spectrum Access (DSA) is one of the potential concepts which can improve the utilization of available spectrum. However, applying DSA in wireless networks can cause undesired characteristics which degrade the performance of the network. For example, the performance of reliable transport protocols such as TCP depends on packet loss rate and variability of round-trip time, which partially depend on frequency band (channel) and interference level in the underlying network. The frequency band and interference levels may vary from time-to-time due to spectrum handoff. Therefore, uncoordinated spectrum handoffs can have significant impact on reliable transport protocols. With DSA, neighbors of a node may rapidly be out of reach when a band in use becomes unavailable as licensed users become active. This can lead to unexpected intermittent connections and performance degradation. Furthermore, the traditional routing protocols require broadcast messages for particular functionalities such as neighbor discovery, route discovery, and route establishment. But due to the lack of a common control channel, the implementation of these functionalities can be very difficult. In order to address adverse effects resulting from DSA, we need to allow coordinated smart decisions to take place across all layers. Since the focus of the cognitive network is to meet end-to-end goals, we believe this concept can be applied to facilitate efficient and effective use of spectrum resources through DSA.

### 4.3.2 Cross-layer Design

Cross-layer design can lead to unintended interactions which may cause system instabilities and performance degradation [2]. A highly coupled cross-layer design may result in inflexibility which hinders future innovations. Therefore, it is important to carefully design and minimize the degree of dependence and exchanged information between non-adjacent layers. Coexistence of cross-layer designs is another issue which needs to be resolved. At the moment, there are several cross-layer designs proposed to improve network performance by controlling overlapping sets of network parameters. In practice, network nodes run multiple applications which concurrently share network resources/functions with common configuration parameters. How can we ensure different cross-layer schemes can concurrently run without adversely interfering with each other? Can we standardize cross-layer design methodologies?

### 4.3.3 Network Security

In current practice, security issues are considered post network design or implementation. In future, we expect wireless networks to become more dynamic and complex. Definitely, it is going to be more difficult to identify security holes. In addition, the implementation of security functions doesn't come for free! There are associated overheads and costs, which may have a significant impact on the network performance (QoS and/or architectural). One of the key questions is how to secure future networks in a reliable and efficient way? We believe that current approaches to solving security issues need to change. Security should be a part of the initial design and not a patch on the final design. For example, throughout the network design process, data and control information passed between communicating layers or nodes should be considered as compromised. With security concerns in mind, properly designed communication protocols should be less vulnerable to attacks. This will help to reduce additional security measures during or after implementation, which in turn reduces overheads/costs and improves network performance.

### 4.3.4 Communication Models

From a network viewpoint, the communication network is conceived as a set of nodes interconnected by links. But wireless networks are broadcast by nature and the concept of “link” does not hold up well. Unfortunately, most models/topologies representing networks at a high level are developed with the notion of point-to-point links. This has led to the development of network functions, such as medium access and routing, which do not fully exploit the potential of wireless networks. We believe that there are two ways to move forward. We could drop the notion of layers over links and then start afresh by jointly considering transmission, medium access, and routing functions together. Or, we could patch the notion of links by incorporating the characteristics which reflect the broadcast nature of wireless media. In this case, we need to find a way of representing all possible links simultaneously.

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# Chapter 5 – HOW DYNAMIC IS THE NEED?

## 5.1 DYNAMICS OF HETEROGENEOUS ENVIRONMENT

The objective of cognitive radio networks is to adapt their operating parameters to the physical and user environment, hence effective design, analysis and evaluation must be based on appropriate models of the environmental dynamics. For example, the quality of links between pairs of nodes changes on a short time-scale due to rapid changes in the propagation characteristics, i.e. fading, which can be largely accommodated through proper waveform selection (interleaving, error-correction coding, etc.). It may be feasible to consider the averaged effects of the fast fading when considering medium time-scale effects, such as the response of the radio and network parameters (e.g. data rate, packet size changes, frequency adaptation, cluster re-organisation) to changes in link connectivity due to relative node mobility, shadowing, interference, etc. On a still larger time-scale, the CRN must respond to variations in user demands and priorities, which may result in changes of bandwidth, protocol, routing, etc. Note that changes at one scale may impact the responses at other time-scales due to the inter-dependence of parameters.

In this section, the time-scales of factors that might be relevant to the operation of cognitive radio networks are considered. Note that this discussion is limited to the factors that are not affected by the adaptivity of the network itself, or of other radio networks with comparable characteristics. Furthermore, the user demands are also dynamic, with cognitive radio networks expected to support voice, real-time and non-real-time data of various data rates, quality of service requirements, importance and urgency. Those characteristics must be considered as the technology advances: the existence of additional dynamic features, such as interference from other adaptive networks and varying user requirements, will impact the context of the cognitive radio network and may lead to complex or chaotic behaviour.

## 5.2 PROPAGATION

The most rapidly varying propagation factor is fast (or multipath) fading, which results from multiple signal components that arrive from different angles. As the transmitter or receiver moves, the amplitude and phase of the combination of these components varies, producing nulls, or fades. The amplitude crosses the 0 dB threshold at a rate approximately equal to $f_m$, where $f_m$ is the maximum Doppler rate, computed as $f_m = v/\lambda$, where $v$ is the relative velocity of the transmitter and receiver, and $\lambda$ is the wavelength [1]. This is approximately independent of whether there are specular multipath components. Deep fades occur less often, especially when there are specular components (Ricean fading). Table 5-1 shows the approximate average interval between fades resulting from this fading mechanism at different frequencies ($f_c$) and velocities ($v$).

**Table 5-1: Average Fade Intervals for Fast Fading.**

| | $f_c$ = 400 MHz | $f_c$ = 800 MHz | $f_c$ = 2 GHz |
|---|---|---|---|
| $v$ = 30 km/h | 90 ms | 45 ms | 18 ms |
| $v$ = 60 km/h | 45 ms | 23 ms | 9 ms |
| $v$ = 100 km/h | 27 ms | 14 ms | 5 ms |

Shadow fading results when most or all of the multipath components are attenuated, such as by a building or mountain, for example. The level-crossing rate, i.e. the rate at which the power level crosses a given threshold from either above or below, is more or less independent of the wavelength over the frequency range of interest, and is typically modelled as approximately 0.2/m, or one fade per 5 m, in urban areas and 0.002/m in suburban areas [2]. Note that this model assumes that the antenna heights are different in the two environments: in the urban area, the antenna height is below the dominant roof height (microcell), whereas in the suburban case, it is above the dominant roof height (macrocell). Table 2 shows the approximate average interval between fades resulting from the slow fading mechanism at different velocities in the two environments.

**Table 5-2: Average Fade Interval for Slow Fading.**

| | Urban | Suburban |
|---|---|---|
| $v$ = 30 km/h | 600 ms | 60 s |
| $v$ = 60 km/h | 300 ms | 30 s |
| $v$ = 100 km/h | 180 ms | 18 s |

For multiple input multiple output communications, the spatial structure of the channel is also important. Measurements in urban environments have shown that the lifetime of the spatial structure is typically in the range 2-6 m [3].

## 5.3 WAVEFORMS

The period for which a transmitter continuously occupies the channel impacts the ability of a secondary user to detect its transmission accurately. For example, GSM time-slots have an interval of 4.5 ms, and different transmitters may emit during adjacent timeslots.

The consistency of the transmitted waveform may also be important for channel sensing, therefore the rate at which the signal is adapted should be considered. For example, variable-rate MIMO precoding is designed to adapt to exploit the spatial diversity available in the channel, which changes with relative motion of the transmitter and receiver. It was demonstrated in [4] that precoding that is based on the actual channel response matrix may change each frame (in this case, 5.2 ms) whereas precoding based on the channel statistics changes less often and may be stable for tens of milliseconds.

## 5.4 INTERFERENCE

There are two distinct sources of interference for a cognitive radio network: infrastructure or background emitters, and foreground emitters that may also be cognitive-type systems. Note that interference sources can equivalently be thought of as primary sources to be avoided. The time-scales of the cognitive-type systems depend on their ability to sense and react to changes in their environments, and hence they respond to one another’s adaptively; there are too many unknowns at this stage of technology development so the time-scales of these foreground emitters are not discussed here; however, these features must be considered in defining the desired behaviour and evaluating the performance of cognitive radio networks.

The time-scales that result from the infrastructure depend on the range of the emitters and the speed at which the mobile platforms move through their coverage areas. The infrastructure emitters are assumed to be static.

Table 5-3 shows interference durations for different types of emitters and mobile platforms. The mobile platform is assumed to remain within range of the emitter for the maximum duration, i.e. twice the emitter range. The ranges used are: rural 30 km, suburban 2 km, urban 1 km, local 50 m (e.g. WiFi).

The land platform speeds used are: pedestrian 4 km/h, slow/medium/fast 30/60/100 km/h. The airborne platforms are assumed to be a helicopter with speed 200 km/h and height 4,000 m, and a jet with speed 1500 km/h and height 11,000 m. The beam-widths on both platforms are taken to be 20º, therefore the footprint from the helicopter is 1,400 m wide and that from the jet is 4,000 m wide. Note that the range of the suburban, urban and local emitters is less than the height of the airborne platforms.

**Table 5-3: Typical Interference Duration for Different Static Emitters and Mobile Platforms.**

| | Rural | Suburban | Urban | Local |
|---|---|---|---|---|
| Pedestrian | 15 h | 60 min | 30 min | 90 s |
| Slow vehicle | 2 h | 8 min | 4 min | 12 s |
| Medium-speed vehicle | 60 min | 4 min | 2 min | 6 s |
| Fast vehicle | 36 min | 144 s | 72 s | 4 s |
| Helicopter | 18.5 min | | | |
| Jet | 2.5 min | | | |

Another source of interference (or primary to avoid) is radar, in particular ground-based weather and air traffic control radars. Assuming both have a beamwidth of 1° and sweep through 360° in approximately 20 s and 4 s then the beam is present for durations of 50 ms and 10 ms for the weather and air traffic control, respectively.

Future systems such as IEEE 802.22 WRANs re-using the analog TV bands have a low degree of dynamic behaviour. It is not anticipated that the TV transmissions will turn on and off with short time-scales, and it would be expected that secondary WRAN systems would similarly have long occupancy times. These time-scales will likely be on the order of hours or days.

## 5.5 TIME-SCALES

The time-scales described above are summarised in Figure 5-1.

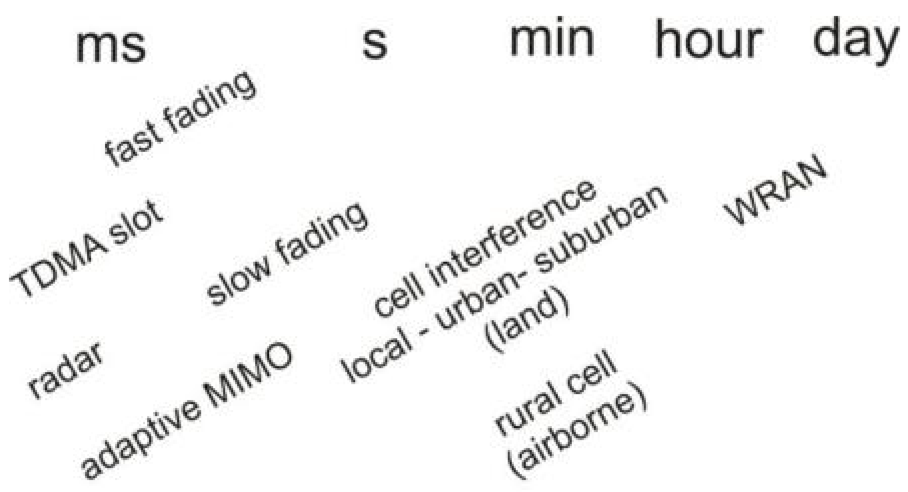


**Figure 5-1: Time-Scales of Dynamic Factors in the Operating Environment.**

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# Chapter 6 – DEFENSIVE AND OFFENSIVE THROUGH COORDINATED DYNAMIC SPECTRUM ACCESS

## 6.1 INTRODUCTION

In the recent years wireless communication has suffered from frequency spectrum scarcity, as newly developed techniques always demanded an additional exclusive spectrum access. Nevertheless, the utilization of the assigned spectrum still only ranges between 15% and 85% [1]. In order to use those remaining spectrum holes, effort was put on achieving Dynamic Spectrum Access (DSA), which required new techniques to adapt to the changing environment.

In return, those new techniques now enable a DSA capable device to autonomously select the best available channel, so it becomes a Cognitive Radio (CR). According to [1], a CR has four main functions: spectrum sensing, spectrum management, spectrum mobility and spectrum sharing. To improve those capabilities, several cognitive radios are grouped to a Cognitive Radio Network (CRN) in order to share spectrum information and therewith provide better spectrum knowledge for each node. This invokes cooperation not only between transmitter and receiver, but between all nodes in the network. Furthermore, coordination between different networks is referred to as Coordinated Dynamic Spectrum Access (CDSA). In contrast to the network-internal cooperation, CDSA does not imply sharing of spectrum information between the networks, but a coordination of actions for not interfering with each other (see Figure 1). This low interference is also interesting for military communication, especially regarding topics like Low Probability of Detection (LPD), Low Probability of Interception (LPI) and Anti-Jamming (AJ) as part of Electronic Warfare (EW).

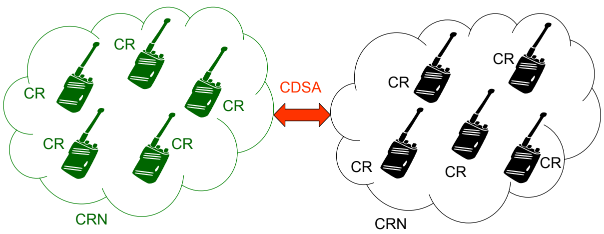


**Figure 6-1: CDSA Between Two CRN.**

This section gives an overview about possible advantages and disadvantages by using CDSA for defensive and offensive measures. As CDSA is a relatively new topic, Section 6.2 will give a short introduction to related work in this area. Section 6.3 summarizes the main components of EW. Finally, Section 6.4 will give an introduction on how to improve LPD, LPI and jamming by the help of CDSA technology, while bearing in mind the vulnerabilities of CDSA. Section 6.5 will conclude the findings and present the next steps.

## 6.2 COORDINATED DYNAMIC SPECTRUM ACCESS

CDSA does not only aim at solving the problems of DSA, but it offers new capabilities for wireless communication. In order to present an overview about this research topic and also to highlight the improvements achieved by coordination, at first DSA is reviewed in Section 6.2.1, and after that in Section 6.2.2 the features of coordinating DSA capable devices are described.

### 6.2.1 Dynamic Spectrum Access (DSA)

According to [2] and [3], DSA can be separated into three models: the *Dynamic Exclusive Use* Model, the *Hierarchical Access* Model and the *Open Sharing* Model.

#### *6.2.1.1 Dynamic Exclusive Use*

Dynamic Exclusive Use deals with regulation of the spectrum by licensing models. A license allows a user to occupy a certain frequency band at a given time in a defined geographic area. Usually those licenses are issued by regulation authorities like the Federal Communications Commission (FCC) in the USA, the Bundesnetzagentur (BNetzA) in Germany or the National Allied Radio Frequency Agency (NARFA), which is responsible for the national military frequency structure. In many cases the licensees do not utilize their spectrum at all times. Consequently, it is proposed to sub-lease these free frequency bands.

This could either be done by allowing the licensee to sell and trade spectrum. Thus a sub-licensee can be given the right to exclusively use this resource without being mandated by a regulation authority. This approach is called *Spectrum Property Rights*, as the license – or the right – is based on the three spectrum properties, frequency band, time and geographic area.

A second approach for the Dynamic Exclusive Use Model is *Dynamic Spectrum Allocation*. For this the temporal and spatial traffic statistics are exploited, which is valuable for long-term applications, such as UMTS or DVB-T. Sub-leasing based on such traffic statistics leads to a much more flexible spectrum allocation than in the previous approach. But again, dynamic is limited to the capabilities of the licensee, so it is unlikely that with either of these approaches the spectrum holes can be optimally filled.

#### *6.2.1.2 Hierarchical Access*

Hierarchical Access is concerned with unlicensed secondary users, utilizing spectrum without interfering with primary users. For this three approaches are known in literature, *Spectrum Underlay*, *Spectrum Overlay* and *Interweave*. All of them have in common that secondary users need to have an overview about the current spectrum in order to detect and identify primary users.

Spectrum Underlay exploits the spectrum by using it despite a primary user transmission, by causing interference only below prescribed limits. Therefore an extremely weak signal is required which only allows transmissions over short distances, but nevertheless a high data rate can be achieved. As an example, Spectrum Underlay is used in Ultra-Wideband (UWB) applications.

Similar to Underlay, Spectrum Overlay allows concurrent primary and secondary user transmission. Here the knowledge about the spectrum is used for some pre-coding at the transmitter in order to diminish the interference at the receiver. This technique is known in literature as *Dirty Paper Coding*.

For not interfering with other signals, Interweave is investigated. This approach intends to use spectrum holes in an opportunistic way *(Opportunistic Spectrum Access)*, meaning that the spectrum is periodically monitored by the secondary user for absence of primary users in order to use the gaps to transmit oneself. An example for this is depicted in Figure 6-2.

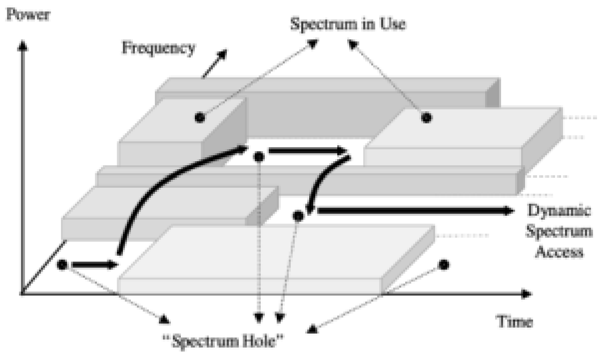


**Figure 6-2: Opportunistic Spectrum Access [1].**

#### *6.2.1.3 Open Sharing*

While the Dynamic Exclusive Use Model and the Hierarchical Access Model assume primary users have a license to use a certain part of the spectrum, the Open Sharing Model assumes a free spectrum with only peer users. Two different approaches on how to organize interference-free communication are discussed: a *centralized sharing strategy*, based on a central coordinator, is first investigated, followed by a *distributed sharing strategy* in which users have to avoid collision by negotiation. In order to achieve optimal spectrum utilization, it is considered to organize Open Sharing based on *game theory*.

#### *6.2.1.4 Advantages and Disadvantages of DSA*

One main advantage of using DSA is that a better utilization of the spectrum is achieved. Moreover secondary users do not need constantly reserved spectrum licensed by a regulation authority. Furthermore DSA allows one to automatically select the best available channel.

Nevertheless, a disadvantage is that problems might occur due to interferences with primary users, caused by the Hidden Station Problem, multipath fading or shadowing.

### 6.2.2 Coordination

As described in Section 6.2.1.4, the main disadvantage of DSA is possible interference with an undetected primary user. Countermeasures against the reasons of this problem (Hidden Station Problem, multipath fading or shadowing) are currently investigated in terms of cooperation between DSA capable devices.

It is important to mention that any kind of dynamic frequency selection, such as the Open Sharing or the Opportunistic Spectrum Access from Section 6.2.1, already requires coordination between transmitter and receiver. Nevertheless, if there are just two devices cooperating with each other, there is only a limited amount of information about the spectrum achievable, especially when they are communicating and their resources are heavily used. Consequently, the capabilities of information sharing between more than two devices are investigated.

#### *6.2.2.1 Cognitive Radio Networks*

In order to coordinate the actions of more than two DSA capable devices, these usually set up a network for initiating a constant exchange of information. This can be either organized in a centralized or a distributed way, similar to the Open Sharing Model (see Section 6.2.1.2). In the centralized approach there is usually a wired backbone, to which the networked devices are connected [6]. In the distributed approach this is most likely a Mobile Ad-hoc Network (MANET).

Information gathered by sensing the spectrum is shared among the networked devices, so that each device gets a precise overview about the spectrum. This can on one hand be done in a way that each device monitors a different frequency band. Thus the community is able to sense a wide part of the spectrum. On the other hand, as the devices are spatially distributed, it is possible to exploit the spatial diversity. If there are many devices in one network, also a combination of those capabilities is imaginable. In a static setup the radios can be organized to transmit data several times in a coordinated way, like it is done in Multiple Input Multiple Output (MIMO) systems, and thus achieve a more robust communication [10]. But also in a dynamic setup a more robust communication can be achieved by intelligently overhearing and retransmitting signals.

Another aspect relevant for CRN, by which communication can be stabilized, is cross-layer architecture. By this the Quality of Service (QoS) in a network can be improved; moreover the effects of cross-layer MIMO can be used in the previously described static setup [5].

##### *6.2.2.2 Coordinated Dynamic Spectrum Access*

CDSA deals with the coordination of non-cooperative networks on the same hierarchy layer, so that they can coexist without interfering with each other. For this, several centralized approaches are already available [7][8]. Those approaches define a frequency broker, which organizes spectrum access in a given region. In [9] a distributed spectrum management approach is described. This distributed approach is not only advantageous regarding performance, it moreover obviates a single point of failure (the central frequency broker), which is important for military usage.

##### *6.2.2.3 Advantages and disadvantages of coordination*

Coordination of devices and networks provides a more precise and detailed overview about the spectrum. As a networked CR device can deduce network conditions from this and immediately adapt to those conditions, interference to primary users can be reduced and the Hidden Station Problem improved. Moreover, as explained before, a more robust communication is established and thus a higher successful transmission probability is achieved. Last but not least, a higher data throughput is attained.

On the other hand, the disadvantage is that the coordination and the robustness require more network-internal traffic due to retransmission. With each implementation a way has to be found how to minimize this internal traffic and moreover not to neglect a primary user because of it.

## 6.3 ELECTRONIC WARFARE (EW)

CDSA can be used for defensive and offensive with regard to EW. In literature four main measures of EW are known: *Signals Intelligence* (SIGINT) mainly used for reconnaissance, *Electronic Support* Measures (ESM), *Electronic Counter Measures* (ECM) and *Electronic Counter Countermeasures* (ECCM) for missions. All of these measures, which are used to protect friendly personnel, facilities, equipment or objectives from being attacked, are part of defensive, while all measures used to attack an adversary are part of offensive.

### 6.3.1 Signals Intelligence (SIGINT)

SIGINT is concerned with the detection and analysis of intercepted signals. In addition to finding signals in spectrum, found signals are also analyzed and categorized. This is done in a twofold way. On one hand communication signals and their information are analyzed (known as *Communication Intelligence*, COMINT); on the other hand the signals are inspected for non-communications information, like e.g. the transmitter location (known as *Electronic Intelligence*, ELINT).

### 6.3.2 Electronic Support Measures (ESM)

ESM (also known as Electronic Support, ES) deals with the detection of electromagnetic radiation frequencies, respectively signals, for the purpose of immediate threat recognition and the tactical employment of forces. While SIGINT is in principle used for long term surveillance and extensive reconnaissance, ESM is focused on a short term mission-specific employment, probably benefitting from the results of SIGINT. In contrast to ECM and ECCM, Electronic Support Measures are completely passive.

### 6.3.3 Electronic Counter Measures (ECM)

ECM (also known as Electronic Attack, EA) is defined as actions taken to prevent or reduce the enemy's effective use of the electromagnetic spectrum. It includes jamming and deception. Jamming is the deliberate radiation or reflection of electromagnetic energy with the object of impairing the deployment of electronic devices, equipment or systems being used by a hostile force. Deception is the deliberate radiation, re-radiation, alteration, suppression, absorption, denial, enhancement, or reflection of electromagnetic energy in a manner intended to mislead a hostile force in the interpretation or use of information received by his electronic systems. Electronic Counter Measures can be either active (e.g. jamming) or passive (e.g. absorption of electromagnetic energy, Faraday cages). All active measures can be detected by an adversary.

### 6.3.4 Electronic Counter Countermeasures (ECCM)

The goal of ECCM (also known as Electronic Protective Measures, EPM, or Electronic Protection, EP) is to protect friendly facilities or personnel against ECM. Also for this there are active (e.g. frequency hopping) and passive (e.g. battlefield tactics) measures, of which the active measures can be detected by an adversary.

## 6.4 DEFENSIVE AND OFFENSIVE THROUGH CDSA

Applying CDSA to EW should result in improving known measures for defensive and offensive, but should also bring up new techniques. Nevertheless, the question remains whether an approach, which is basically used for setting up a robust communication without interfering with other signals, might also useful for attack measures like e.g. jamming. Consequently, the capabilities offered by CDSA need to be analyzed regarding this new purpose.

On the other hand EW can also be used especially against CDSA-capable networks, as their adaptability and dynamic cause vulnerabilities. Consequently it must be analyzed how CDSA-capable networks can be attacked and how they can be protected.

### 6.4.1 Defensive and Offensive against legacy devices

As already pointed out in Section 6.2.2.2, CDSA implies the availability of multiple, spatially distributed devices. These devices are organized in a cognitive network and thus have the ability to exchange their knowledge about the spectrum.

This exchange of knowledge leads to a more precise and detailed overview about the spectrum and its current occupancy for each device, which is directly valuable for ESM. As moreover a multitude of processing elements is available with the devices, a more effective and comprehensive analysis and categorization of the detected signals, than with conventional equipment, can be achieved. Thus SIGINT is supported. Detection and categorization even can be improved by utilizing the spatial diversity of the devices. Not only can the spectrum be observed at different places at the same time, the gathered information might also help to locate a transmitter by comparing the Time of Arrival (ToA) of his signal at miscellaneous devices. The latter case is also part of SIGINT and requires perfect time synchronization and exact location information for each device.

Furthermore, as a basic feature of CDSA, dynamic access to the spectrum can be utilized for active ECCM. Again the precise spectrum overview, and thus also the information about holes and the ability to hop to them, lead to a robust and interference-free transmission. In addition to that, overlay and underlay (see Section 6.2.1.2) might be used to hide a signal from being detected (LPD) and intercepted (LPI). Apart from this, also the potential of CDSA to reach a higher throughput allows a signal to be in space for a shorter time, and thus to reduce its vulnerability.

Another basic feature of CDSA is the adaptability to network conditions. This means that CDSA capable devices can react on given occupations or changes in the spectrum by adapting their communication (e.g. by hopping to another frequency) spontaneously. This is only limited by the ability of those devices to arrange changes among both transmitter and receiver. But if successful, then this adaptability provides the prerequisites for circumventing jamming attacks (Anti-Jamming as part of active ECCM). Anyway it promises a higher successful transmission probability.

Moreover this adaptability can also be used for active ECM. Given, that the spectrum occupancy is known and adversary signals have been identified and classified, intelligent countermeasures against those signals can be carried out, e.g. by deception. Considering furthermore the ability to sense a wide part of the spectrum due to parallel sensing of several devices, it also has to be investigated how broadband jamming can be organized among the devices. Thus CDSA is also usable for attack measures.

### 6.4.2 Defensive and Offensive against CDSA-capable networks

The main aim of a CDSA-capable network is to find and use the best available channel for a transmission. If there is nothing to transmit, the channel might be taken over by another network. This is basically acceptable, as coordination between different networks usually implies a fair spectrum usage[1] with thoughtfulness regarding other users. But especially in military applications it might be important to always have the required spectrum, be it due to high priority information or due to a high amount of data which must be transmitted in a short time. Thus it must be possible to defend the already assigned spectrum against a takeover by other users (both friendly and hostile forces) or to even conquer spectrum that is assigned to other users. This can either be done by using the same EW techniques as against legacy devices or by exploiting the vulnerabilities of CDSA-capable networks.

Those vulnerabilities might differ from network to network. One well-known example for this is Primary User Emulation (PUE) [12], in which a secondary user emulates the properties (waveform, signal strength, etc.) of the primary user signal in order to make other secondary users believe the primary user is transmitting and therefore free the channel. There may be systems capable of detecting the emulation and thus do not free the channel. Consequently, as a first step for defensive and offensive against CDSA-capable networks, their vulnerabilities must be revealed. This comprises the detection of single points of failure, like a static coordination channel, as well as the reaction of a whole network to disturbances. An example of the latter case is to act offensively by, for instance, increasing the transmission power or changing the waveform and to observe the reactions of other systems. Thus information about the vulnerabilities of other CDSA-capable networks can be collected.

Attacking those networks means to exploit the detected vulnerabilities. Possible active measures are *Denial of Service* (DoS) attacks [11] like e.g. jamming a coordination channel of a network, which will completely terminate the communication between transmitter and receiver, or PUE attacks, which should cause the current users to leave the attacked channel.

[1] The most common technique for achieving fair spectrum usage is game theory (see also Section 6.2.1.3). Consequently in a next step game theory itself has to be analyzed regarding vulnerabilities.

Protection of a CDSA-capable network consequently requires a limitation of those vulnerabilities. This could mean not to use an easily detectable coordination channel or to discover a PUE attack and to react accordingly.

If being detected is less important than possessing the best available channel, then it must be considered whether that channel should be defended from being taken over by other users. In addition to the so far described protection against attacks, it might be helpful not to free that channel when there is no information to transmit. Sending random data will occupy the channel, so that other users will recognize the channel as already assigned and select different channels for their transmissions.

### 6.4.3 Advantages and disadvantages

By applying CDSA to EW, several advantages can be noticed. Not only does military communication become more robust, also the QoS can be improved. Last but not least, CDSA enables more dynamic and adaptive attack measures.

Nevertheless, some disadvantages, or vulnerabilities, are to be considered when using the dynamics and adaptability of CDSA. But for most of them there are solutions how to mitigate them.

## 6.5 CONCLUSION AND OUTLOOK

This article described some first ideas how to use CDSA for defensive and also offensive measures, against both legacy devices and other CDSA-capable networks. CDSA can provide improvements for nearly all parts of EW because of its ability to coordinate the properties of multiple adaptive devices.

In a next step the presented ideas need to be analyzed in detail regarding their technical and operational restrictions. Based on this, an approach has to be developed how these ideas can be implemented. Finally the advantages need to be compared with legacy implementations.

## 6.6 ACKNOWLEDGMENTS

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# Chapter 7 – TECHNICAL SOLUTIONS FOR COGNITIVE RADIO SYSTEMS

## 7.1 THEORY VS. REALITY FOR SPECTRUM SHARING

There is a huge volume of published literature dealing with "optimisation" for spectrum sharing and dynamic spectrum access. This suggests that there is set of conditions that can be identified as "optimal" and that they can be found by mathematical analysis. However, the formulation of each optimisation problem needs to be examined carefully as many common assumptions, both stated and hidden, are violated in real systems. Very little work has been reported to-date that investigates the impact of violating these assumptions, but prior experience suggests that in many cases the "optimal" conditions are not robust.

The first assumption that is made, in almost all analyses of the spectrum sharing problem, is that system performance can be equated with the Shannon capacity. In some sense, the capacity measure does give an upper bound on the potential throughput, but for many more practical system models, the upper bound is so loose as to be useless.

The Shannon capacity itself is based on assumptions that are generally unrealisable in practical communication systems: possibly infinitely long code words and sufficiently sophisticated channel encoder and decoder to provide an error-free channel; and a Gaussian distributed signal. In real systems, the signal distributions are rarely approximated as Gaussian, hence the key capacity assumption is violated. Furthermore, the performance objective in real communication systems is to control errors, not to provide theoretically error-free channels.

It was shown in [1] that optimising using a capacity objective for optimisation of OFDM parameters led to resource allocation strategies that are quite suboptimal for real signal constellations, and that better throughput and more efficient power use could be achieved if the characteristics of the actual signals were taken into account.

In [5], the characteristics of real signals were considered for resource allocation in a spectrum sharing problem. Two pairs of users iteratively allocate resources (power and data) over three channels. Each user has the same total amount of power available. The received signals for the two users on channel *k* are given by:

$$\begin{bmatrix} y_1(k) \\ y_2(k) \end{bmatrix} = \begin{bmatrix} h_{11}(k) & h_{12}(k) \\ h_{21}(k) & h_{22}(k) \end{bmatrix} \begin{bmatrix} \sqrt{P_1} & 0 \\ 0 & \sqrt{P_2} \end{bmatrix} \begin{bmatrix} x_1(k) \\ x_2(k) \end{bmatrix} + \begin{bmatrix} \upsilon_1(k) \\ \upsilon_2(k) \end{bmatrix}$$

where $P_i(k)$ is the transmit power allocated by user $i$ on channel $k$, $\upsilon_i(k)$ is the additive white Gaussian noise and the transmitted signals satisfy $E\{|x_i(k)|^2\}=1$ for $i=1,2$ and $k=1,2,3$. For each channel realization, the responses of the direct paths, $h_{11}(k)$ and $h_{22}(k)$, are drawn from the complex normal distribution $CN(0,1)$, while the interfering path responses, $h_{12}(k)$ and $h_{21}(k)$, are drawn from $CN(0,\beta)$, where $\beta<1$. The receivers are assumed to have perfect channel knowledge of the direct path, and are able to accurately estimate the interference and noise powers.

The real signals used by each user pair considered here are DSSS and OFDM on each of the three channels. Over the three channels, this can be considered as a MC-DSSS signal and an OFDM signal, where 200 of the OFDM tones are used on each channel. Both these signals are intended for frequency-selective channels, but flat fading is considered here to limit the number of parameters considered, as a way to illustrate more clearly the resource allocation problem.

The first user transmits using OFDM, and uses the same modulation constellation on all tones within channel *k*. The set of modulation strategies available is $R_1$ = {BPSK, QPSK, 8-PSK, 16-QAM, 64-QAM}. The second user transmits with DSSS using BPSK, and has a set of strategies based on the spreading factor (SF), $R_2 = \{SF = 1, 3, 7, 15, 31, 63\}$, where m-sequences are used for spreading. The target bit error rate (BER) for both users is $10^{-3}$.

Two resource allocation algorithms are considered. The first is the iterative water-filling algorithm that allocates each user's total power to the three channels in such a way as to maximise the user's Shannon capacity. Each user's signal is considered to be Gaussian distributed, hence the combination of noise and interference is treated as Gaussian. This is the approach to resource allocation that is widely used under the terminology "game theory". When the algorithm has converged, the received signal power, interference and noise is used to determine the data rate (OFDM modulation or DSSS spreading factor) that can be supported at the target BER.

The second algorithm is a greedy algorithm, in which each user applies power in increments to each channel in such a way as to maximise power efficiency. This is achieved by pre-computing lookup tables of the amount of received signal power required to obtain the target BER with different levels of interference and noise for each strategy in the sets $R_1$ and $R_2$. The increment in transmitted power necessary to increase the data rate by one step is computed for each channel, and the allocation is given to the channel that achieves the highest power efficiency.

Figure 7-1 shows the rates achieved by the two algorithms, averaged over 10,000 simulations with Rayleigh fading on each channel. It is clear that the greedy algorithm achieves a higher rate over all SNRs than the allegedly optimal water-filling algorithm. This is because (a) the interference is not, in fact, Gaussian distributed and hence does not have the same effect as the noise and (b) the constellation sizes are discrete, and as shown in [1], the required power is therefore also discrete. Note that the rates plateau due to the finite size of the rate sets $R_1$ and $R_{2;}$ this is particularly noticeable for the DSSS, where the shortest spreading factor dominates even at a relatively low SNR.

The equivalent figure for two OFDM users, both using rate strategy sets $R_{1,}$ is shown in Figure 7-2, in which the greedy algorithm again outperforms the water-filling algorithm. At high SNRs, the increasing mutual interference in the water-filling case results in a reduction in the achievable rates, whereas the greedy algorithm allocates only enough power to achieve the target BER.

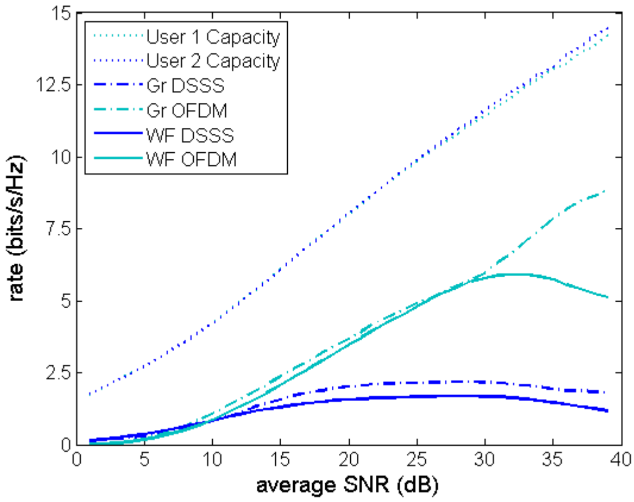


**Figure 7-1: Rates for Resource Allocation Algorithms with DSSS and OFDM Users.**

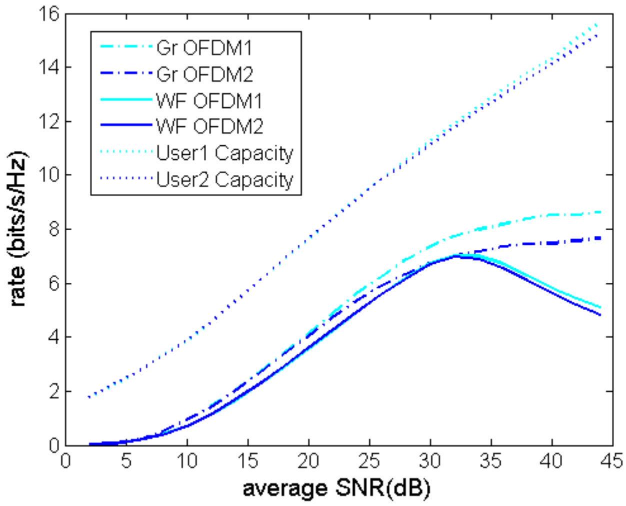


**Figure7-2: Rates for Resource Allocation Algorithms with Two OFDM Users.**

An interesting feature of the resource allocation problem is overlooked in the literature applying game theory and iterative water-filling. When the system becomes interference limited, i.e. at moderate and higher SNRs, power applied by each user is just countering the effects of interference from the other user without supporting higher rates. This extra power is wasted. It is quantified in Figure 7-3. This is a particular problem with the water-filling algorithm, which allocates all the available power across the channels regardless of whether it is needed to support the data rate. In contrast, the greedy algorithm applies only as much power as is required to achieve the target BER; the remaining power is unallocated. The unused power is also shown in Figure 7-3. Note that a small amount of power is wasted in the greedy algorithm because, in about 25% of cases, the algorithm alternates between two solutions; hence at the stopping point an equilibrium has not been reached.

This over-allocation of power is significant it creates an unnecessarily large spectral footprint, which means that other pairs of users, outside the spectrum sharing game being considered, cannot access the spectrum.

This is counter to the objective of increasing the number of users accessing the spectrum, and the overall spectral efficiency.

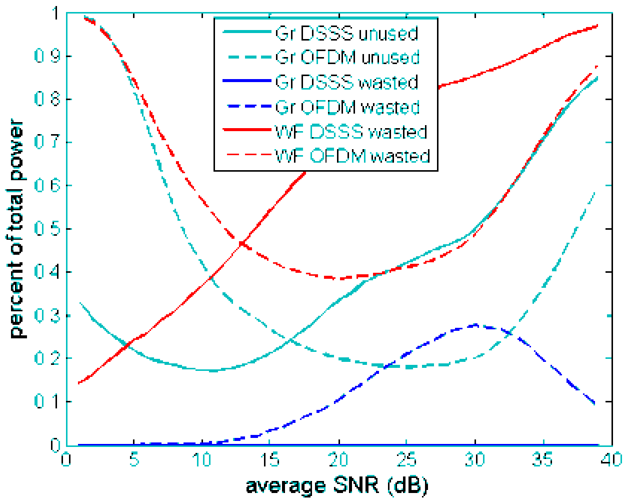


**Figure 7-3: Power Usage for Resource Allocation Algorithms for DSSS and OFDM Users.**

When both user pairs transmit with OFDM, Figure 7-4, the wasted power allocated by the water-filling algorithm exceeds the power unused in the greedy algorithm.

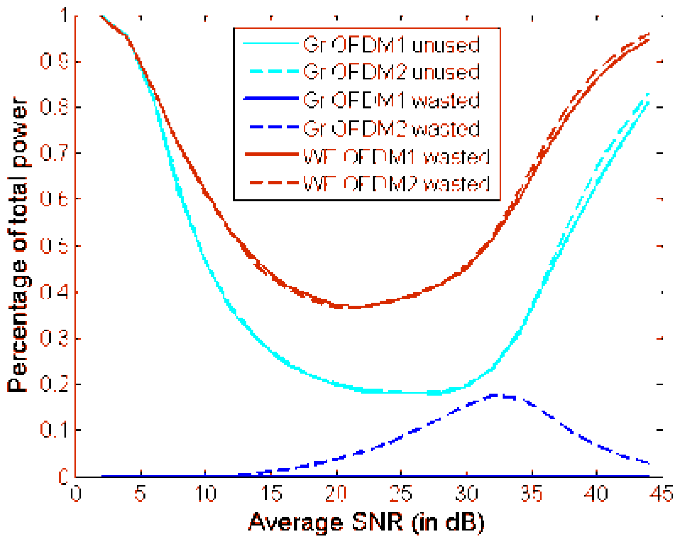


**Figure 7-4: Power Usage for Resource Allocation Algorithms for Two OFDM Users.**

### 7.1.1 Additional Challenges

In the context of spectrum sharing, one of the assumptions most commonly made, but always violated, is the availability of perfect state information. In a system with noise, perfect channel state information is impossible to obtain. Mobility, quantisation and feedback introduce more errors.

Experience shows that taking into account that channel state information is imperfect can robustify communications systems, leading to better overall performance. This has recently been illustrated in the case of spectrum sharing in [4]. In other contexts, similar approaches have been fruitful, for example, in different MIMO signalling approaches [2], [3]. Typically, the analysis incorporates the second order statistics of the estimation error: it can be challenging, however, to set up a tractable problem and care must be taken to ensure that further, unreasonable assumptions are not introduced.

### 7.1.2 Challenges for NATO CR Work

While there has been a lot of material published on the topic of spectrum sharing and dynamic spectrum access, it is predominantly analytic. Analytical approaches are often too complex without unrealistic assumptions. By the very nature of academic publishing, evaluations of real system considerations are not common, and authors are encouraged to make unrealistic assumptions in order to make their problems tractable and their analyses elegant.

For the purposes of considering the impact and performance benefits of CR in real systems, it is important to remember that just because something is published does not mean it is true or relevant or useful.

The work considered thus far has focused on the PHY and MAC layers, but it is necessary also to consider the impact of the network and higher layers on the overall problem of spectrum sharing.

It is clear that more work is required to determine appropriate strategies for real systems. The first step is to strip away the unrealistic assumptions used in theoretical analyses to develop approaches that withstand the transition to practical systems. The majority of papers to-date in the literature represents work that is too theoretical for real application. Systems built upon these analyses will not perform as claimed, and will not be robust to degradations and deficiencies. Further, these will be the future legacy systems that the next generation will have to work around.

## 7.2 GAME THEORY

The coexistence problem between multiple CR systems and eventually primary users is a challenging decisional task since a centralized and coordinated approach is often unavailable. When distributed decisions are envisaged, the powerful mathematical framework of game theory [9] can be successfully applied. In literature, the analysis of the interference generated by multiple cognitive radios has often been realized by making use of game theoretic approaches in which the cognitive radios are modeled as the players of a game [1]. In this context, they make decisions in their own self-interest by maximizing their utility function, while influenced by the others players' decisions. Generally, the different controllable transmission parameters in the communication (e.g. transmission power, frequency channel, etc.) represent the strategies that can be taken by the players, and the utility of the game is a function of e.g. the signal to interference and noise ratio (SINR) or the throughput. In this document we propose a coalition deployment, in which multiple platoons of soldiers from different nations, equipped with cognitive radios, share a certain set of frequency channels to operate. In the system proposed, decisions are taken in a distributed way by the cognitive radios according to the maximization of their individual utility. These decisions strongly depend on those made by the other radios, since the performances are limited by the aggregated interference generated by all the cognitive radios simultaneously transmitting in a certain band. We present two different games based on the theory of supermodular [7] and potential games [11]. These two classes of games have particularly favorable convergence characteristics, since it can be shown that under certain circumstances, there always exist a pure Nash equilibrium – NE - (i.e. an equilibrium point from which no player has interest in unilaterally deviating) and convergence to it is guaranteed.

### 7.2.1 S Modular Games

This section shows the potential benefits of the adoption of a cognitive radio strategy formulated according the mathematical discipline of game theory, with particular reference to S-modular games [7]. Such attractive feature provides the flexibility and the efficient adaptation to the operative environment that were previously mentioned. S-modular games have been used for power allocation in cellular networks by Altman and Altman in [8]. This section extends their results in the case a CR dislocation of transmitters and receivers, as well as proposes a new allocation strategy for multi-carrier allocation.

Game theory provides a set of powerful tools in order to predict the evolution of dynamical multiple decisional entities operating in the same context. One relevant key classes of games are the supermodular games (S-games).

We focus our attention to a set of $N$ users playing on a strategy space $S$. It means that each element of $S$ represents the possible choice of all players at a given time of the play. Introduced by Topkis in [1], S-games are normal form games $\Gamma = \left\{N, \{S_i\}_{i \in N}, \{u_i\}_{i \in N}\right\}$ where $N$ is the set of users, $S$ the strategy space, $f_i$ the set of utility functions and $\forall i \in N$ these conditions are satisfied:

1) the strategy space $S_i$ of user $i$ is a complete lattice.

2) 2. $u_i$ is supermodular in $s_i$.

3) 3. $u_i$ presents increasing differences in $x$.

Supermodularity of a function $u : X \to \Re$ when $f_i$ is twice differentiable, is satified by the following condition:

$$\frac{\partial^2 u_i(x)}{\partial x_i \partial x_j} \geq 0 \tag{1}$$

for all $x \in S$ and $i \neq j$.

The increasing differences property defined in [7] when applied to utility functions is relevant to the cognitive radio problem. If the strategy space is the allocated power on the radio channels/sub-carriers and the utility function is related to the SINR experienced by users, an increased power floor from other users results in a increased power of the desired one.

All the users play with the same strategic rational behavior, following the so-called *best response* (BR) decision rule, defined as for each $i$:

$$BR_i(x_{-i}) = \max[\arg\max_{x_i \in S_i} u(x_i, x_{-i})] \tag{2}$$

The BR decision is a distributed one as it is taken independently from each user. The evaluation of the utility function requires the complete knowledge of the choices operated previously from other users $x_{-i}$. In practical implementations the visibility of others is limited to the effectiveness of the sensing functions available in the cognitive radio system as described in [1].

When the cited conditions are met, the S-modular game is proven to have a unique NE point and to show a monotone convergence to it when the BR decisions is operated by the users.

A slightly more complicated scenario is found when the strategy set for each user depends from the choices of others, i.e. when $S_i = S_i(x_{-i})$. In this case if the policy set $S_i$ is convex and exists a fesible choice $x$ so that $x_i \in S_i(x_{-i})$ and for each user $i$, $BR_i(x_{-i}) > 0$, we obtain the uniqueness of the NE and the convergence to it for the random or round-robin updating rule.

In the coexistence scenario, each user is characterized by a transmitter site $TX_i$ and a receiver site $RX_i$. In the most general context we consider the transmitters and the receivers positions to be completely independent of one another. The utility function for each user is represented by its instantaneous SINR, defined as:

$$\gamma_{i,c} = 10\log_{10}(g_{i,i,c}a_{i,c}) - 10\log_{10}(\sum_{k \neq i} g_{k,i,c}a_{k,c} + \eta_i) \tag{3}$$

where $a_{i,c}$ is the power allocated from the transmitter $i$ ($TX_i$) on the sub-carrier $c$, $g_{j,i,c}$ is the instantaneous channel response from $TX_j$ to $RX_i$, while $\eta_i$ is the AWGN component at $RX_i$. We consider the following utility functions:

$$u_i(a_i, a_{-i}) = \sum_{c=1}^{M} -\left(\gamma_{i,c}(a_i, a_{-i}) - \gamma_{i,c}^*\right)^2 \tag{4}$$

where $\gamma_{i,c}^*$ is the target SINR for user $i$ and sub-carrier $c$. The adopted channel model is composed by a small scale fading and a path-loss component. Two possible stategies of play are applied: the multiple carrier allocation and the best carrier allocation. With the former, the decision leads to the selection of the best response combination of sub-carriers powers, given the previous allocation of other users. The strategy space is a convex sub-lattice of $\Re^m$, i.e. $a_i \in S_i \in \Re^m$ and $0 \leq a_{i,c} < a_{i,MAX}$, for each $c = 1, \ldots, M$. A decision is taken by a randomly chosen user at each stage of the game, following the *best response* rule:

$$BR_i(a_{-i}) = \arg\max_{a_i \in S_i} u_i(a_i, a_{-i}) \tag{5}$$

With the best carrier allocation, the selected user first select the best allocation for each possible carrier, then select the carrier where she receives the best response. In other words:

$$\forall c \in C_i$$

$$a_{i,c}^* = \arg\max_{a_{i,c} \in S_{i,c}} u_i(a_{i,c}, a_{i,-c}, a_{-i}) \tag{6}$$

$$BR_i^*(a_{-i}) = \arg\max_{c \in C_i} u_i(a_{i,c}^*, a_{i,-c}, a_{-i}) \tag{7}$$

where $C_i$ is the sub-carriers set, $a_{i,c}$ is the power allocation on carrier $c$ and $a_{i,-c}$ is the power allocation of all the carriers except $c$.

In the case of imperfect sensing of the radio environment, the action taken by players lead to a sub-optimal outcome of the game.

The proposed scheme is part of the class of distributed resource managers and implies a complete knowledge of the previous allocation step (also derived from sensing). The two presented approaches differ substantially from the complexity point of view. The multiple carrier allocation strategy involves a $M$ -dimensional maximization process to be performed by each user at each game step (recall $M$ is the number of carriers). The best carrier allocation is obtained through $M$ one-dimensional maximizations followed by a sorting operation.

S-modular games can be applied successfully to the power allocation problem when distributed methods are required. In the CR context, the potentials of these game theory tools are more relevant than in other scenarios due to the desired independence of cognitive transmitters. S-modular games are proven to be stable, always converging to NE and completely distributed. The analyzed methods provide good allocations even in the case of multi-dimensional resource space.

### 7.2.2 Potential Games

In this section we refer to the paradigms for cognitive radio introduced in [12], i.e. the underlay and overlay. On the one hand, the underlay paradigm mandates that concurrent transmissions of cognitive radios may occur as long as the aggregated interference generated by the CRs is below some acceptable threshold [10]. On the other hand, the overlay paradigm allows the coexistence of simultaneous communications in the same frequency channel, as long as the cognitive radios somehow facilitate other radios, for example by means of advanced coding or cooperative techniques. We propose cooperation of cognitive radios (overlay approach) to significantly reduce the interference at the cognitive radios' receivers. The performance is analysed using game-theoretic tools, already proven good at modelling interactions in decision processes. In particular, we define two games, underlay and overlay, which can be formulated as exact potential games converging to a pure strategy NE solution, and we compare the overlay to the underlay scheme to learn advantages and drawbacks of the proposed approach.

We consider a coalition deployment in which there are two platoons of soldiers, potentially belonging to different nations. The two platoons consist of $N$ transmitting-receiving pairs, respectively, and with transmission power levels $p_j^i, j=1,...,N, i=1,2$. The cognitive radios of each platoon are in charge of sensing the channel conditions and of choosing a transmission scheme which does not disrupt the communication of the other users. According to the underlay paradigm, a cognitive radio selects the frequency channel and the transmission power level to maximize its satisfaction while at the same time not causing harmful interference to other cognitive radios. On the other hand, based on the overlay paradigm, besides selecting the transmission power and the frequency channel, the cognitive radios devote part of their transmission power to relaying the transmission of the primary user (PU). As a result, the transmission power level is split in two parts, 1) a power level $p_j^{i'}, j=1,...,N, i=1,2$ for its own transmission, and 2) a cooperation power level $p_j^{i''}, j=1,...,N, i=1,2$ for relaying the PU's message on the selected band, where $p_j^i = p_j^{i'} + p_j^{i''}$. The cooperative transmission scheme is arranged as described in [13].

As in the previous section, we model this problem as a normal form game, which can be mathematically defined as $\Gamma = \left\{N, \{S_i\}_{i\in N}, \{u_i\}_{i\in N}\right\}$, where $N$ is the finite set of players (i.e. the $N$ CRs of a certain platoon), and $S_i$ is the set of strategies $s_i$ associated with player *i*. We define $S = \times S_i, i \in N$ as the strategy space and $u_i : S \rightarrow \Re$ as the set of utility functions that the players associate with their strategies.

In the following we introduce two games, representative of the underlay and overlay paradigms and we formulate them as exact potential games.

**Underlay Game**

The strategies for player $i \in N$ in the underlay game are:

1) a power level $p_i^2$ in the set of power levels $P^2 = \left(p_1^2, ..., p_m^2\right)$;

2) a channel $c_i$ in the set of channels $C = \left(c_1, ..., c_l\right)$.

These two strategies can be combined into a composite strategy $s_i = \left(p_i^2, c_i\right) \in S_i$.

The utility of each player *i* of this game, where $i = 1, ..., N$ is defined as follows:

$$u\left(s_i, s_{-i}\right) = -\sum_{j=1}^{N} p_i^2 h_{ij}^{21} f\left(c_i, c_j\right) - \sum_{\substack{j=1 \\ j \neq i}}^{N} p_j^2 h_{ji}^{22} f\left(c_j, c_i\right) - \sum_{\substack{j=1 \\ j \neq i}}^{N} p_i^2 h_{ij}^{22} f\left(c_i, c_j\right) + b \log\left(1 + p_i^2 h_{ii}^{22}\right) \quad (8)$$

where $h_{ij}^{21}$ is the channel gain between transmitter *i* in platoon 2 and receiver *j* in platoon 1; $h_{ij}^{22}$ and $h_{ji}^{22}$ are the channel gains between different transmitting-receiver pairs in the same platoon and, finally, $h_{ii}^{22}$ is the channel gain between a transmitting receiver pair in platoon 2. In addition,

$$f\left(c_i, c_j\right) := \begin{cases} 1 & if\ c_i = c_j \\ 0 & if\ c_i \neq c_j \end{cases} \quad (9)$$

The expression presented in (1) consists of four terms. The first and the third terms account for the interference the *i*-th CR of platoon 2 is causing to the other CRs in both the platoons, simultaneously operating in the same frequency channel. The second term accounts for the interference received by player *i* from the CRs simultaneously operating in the same frequency channel. Finally, the fourth term only depends on the strategy selected by player *i* and provides an incentive for individual players to increase their power levels. In fact, it is considered that the player's satisfaction increases logarithmically with its power. We weight this term by a coefficient *b* to give it more or less importance than the other terms of the utility function.

**Overlay Game**

The strategies for a player *i* in the overlay game are:

1) a power level $p_i^2$ in the set of power levels $P^2 = \left(p_1^2, ..., p_m^2\right)$;

2) a power level $p_i^{2'}$ that the player devotes to its own transmissions, in the set of power levels $P^{2'} = \left(p_1^{2'}, ..., p_q^{2'}\right)$, where *q* is the order of set $P^{2'}$;

3) the cooperative power level $p_i^{2''}$ that the player devotes to relaying a PU transmission and which is computed as $p_i^{2''} = p_i^2 - p_i^{2'}$. The set of this power levels, $P^{2''}$, is the same as $P^{2'}$;

4) a channel $c_i$ in the set of channels $C = (c_1, ..., c_l)$.

These can be combined into a composite strategy $s_i = \left(p_i^2, p_i^{2'}, p_i^{2''}, c_i\right) \in S_i$.

The utility of each player *i* of this game is defined as follows:

$$
\begin{aligned}
u(s_i, s_{-i}) &= -\sum_{j=1}^{N} p_i^{2'} h_{ij}^{21} f(c_i, c_j) \\
&-\sum_{\substack{j=1 \\ j\neq i}}^{N} p_j^{2'} h_{ji}^{22} f(c_j, c_i) - \sum_{\substack{j=1 \\ j\neq i}}^{N} p_i^{2'} h_{ij}^{22} f(c_i, c_j) \\
&+b\log\left(1 + p_i^{2'} h_{ii}^{22}\right) + \sum_{j=1}^{N} p_i^{2''} h_{ij}^{21} f(c_i, c_j)
\end{aligned}
\tag{10}
$$

The expression presented in (2) consists of five terms. Four of them can also be encountered in the underlay utility function. The last term, is a positive contribution to the utility of the player and accounts for the benefit provided to platoon 1 by the relaying realized by the CRs. This term is positively defined to encourage CRs to cooperate.

Both the underlay and overlay games can be shown to be exact potential games, since there exists a function $Pot : S \to \Re$ such that for all $i \in N$, all $s_i \in S_i$, and all $s_i^{'} \in S_i$,

$$
Pot(s_i, s_{-i}) - Pot(s_i^{'}, s_{-i}) = u(s_i, s_{-i}) - u(s_i^{'}, s_{-i}) \tag{11}
$$

The function Pot is called exact potential function of the game Γ.

The potential function reflects the change in utility for any unilaterally deviating player. As a result, if *Pot* is an exact potential function of the game Γ, and $s^* \in \left\{\arg\max_{s^{'} \in S} Pot\left(s^{'}\right)\right\}$ is a maximiser of the potential function, then s* is a NE of the game. In particular, the best reply dynamic converges to a NE in a finite number of steps, regardless of the order of play and the initial condition of the game, as long as only one player acts at each time step, and the acting player maximizes its utility function, given the most recent actions of the other players.

For the previously formulated underlay and overlay games, we can define two exact potential functions, $Pot_u(S)$ and $Pot_o(S)$:

- *Underlay game Potential Function:*

$$
\begin{aligned}
&Pot_u(S) = Pot_u(s_i, s_{-i}) \\
&= \sum_{i=1}^{N}\left(-\sum_{j=1}^{N} p_i^2 h_{ij}^{21} f(c_i, c_j)\right) \\
&+\sum_{i=1}^{N}\left(-a\sum_{\substack{j=1 \\ j\neq i}}^{N} p_j^2 h_{ji}^{22} f(c_j, c_i) - (1-a)\sum_{\substack{j=1 \\ j\neq i}}^{N} p_i^2 h_{ij}^{22} f(c_i, c_j)\right) \\
&+\sum_{i=1}^{N} b\log\left(1 + p_i^2 h_{ii}^{22}\right)
\end{aligned}
\tag{12}
$$

- *Overlay game Potential Function:*

$$\begin{aligned} Pot_o(S) &= Pot_o(s_i, s_{-i}) \\ &= \sum_{i=1}^{N}\left(\sum_{j=1}^{N}\left(p_i^{2"} - p_i^{2'}\right)h_{ij}^{21} f\left(c_i, c_j\right)\right) \\ &+ \sum_{i=1}^{N}\left(-a\sum_{\substack{j=1 \\ j\neq i}}^{N} p_j^{2'} h_{ji}^{22} f\left(c_j, c_i\right) - (1-a)\sum_{\substack{j=1 \\ j\neq i}}^{N} p_i^{2'} h_{ij}^{22} f\left(c_i, c_j\right)\right) \\ &+ \sum_{i=1}^{N} b\log\left(1 + p_i^{2'} h_{ii}^{22}\right) \end{aligned} \quad (13)$$

The proof that the underlay and overlay games, with the utility functions defined in (1) and (2) and with the potential functions defined in (4) and (5), are exact potential games is given in [10], together with an extensive performance evaluation.

## 7.3 ITERATIVE WATER FILLING

### 7.3.1 Coexistence of Multiple Cognitive Tactical Radio Networks Using an Iterative Water Filling Based Algorithm

The objective of this section is to provide a distributed power allocation for multiple cognitive tactical radio networks coexisting in the same area. The transmitter of each tactical radio network broadcasts the same information to its group (voice, data...). This objective calls for a synergy between different areas:

- Cognitive radio [1][15]: A wireless node or network can adapt to the environment by changing its transmission parameters (frequency, power, modulation strategy).
- Broadcast channel with only common information [16][17][18]: A tactical radio network is a network in which information is conveyed from one transmitter to multiple receivers. Most of the literature on broadcast channels covers the transmission of separate information to the different receivers or the transmission of both separate and common information to the different receivers over parallel channels [19][20][21][22][23][24].
- Distributed multi-user power control [25][26][27]: Autonomous power allocation in the frequency domain by iterative water-filling for interference channels. By considering the interference of the other users as noise, iterative updates of the power allocation for each user reach an equilibrium.

The water-filling strategy has been initially designed for a single transmitter and a single receiver over multiple sub-channels [28]. The water-filling strategy can maximize the rate of the link subject to a power constraint (inner loop), but can also minimize the power subject to a rate constraint (outer loop). In the first part of this section, we extend the water-filling strategy to multiple receivers by considering parallel broadcast channels with only common information (parallel multicast channels) and assuming perfect Channel State Information (CSI) at the transmit side. In this case, the extended water-filling strategy maximizes the minimum rate subject to a power constraint (inner loop) or minimizes the power subject to a minimum rate constraint (outer loop). However, finding a solution to these problems for parallel multicast channels is not straightforward. Moreover, standardization often defines a spectral mask that each transmitter has to satisfy. Therefore, we propose to use an utility function based on the weighted sum of the possible achievable rates to the receivers for the inner loop and to find the best set of weights that minimizes the power subject to a minimum rate constraint for all receivers and a spectral mask constraint.

In the second part of this section, capitalizing on the previous results, we introduce an autonomous dynamic spectrum management algorithm based on iterative water-filling for multiple cognitive tactical radios [25]. In the iterative water-filling algorithm, each network considers the interference of all other networks as noise and performs a water-filling strategy. The power spectrum of the network modifies the interference caused to all other networks. This process is performed iteratively until the power spectra of all networks converge. The main novelty is the extension of the iterative water-filling algorithm to multiple receivers for the coexistence of multiple cognitive tactical radio networks. The transmitter of each tactical radio network takes into account the spectrum sensed by all its receivers and iteratively updates its power spectrum until all the constraints are satisfied in each network, i.e. minimum rate and spectral mask constraints. Simulation results compare our strategy with the *worst receiver* strategy for the minimization of the power subject to a minimum rate constraint.

#### *7.3.1.1 Single tactical radio network*

Consider a $T$ -receiver $N_c$ parallel fading Gaussian broadcast channel as shown in Figure 7-5:

$$y_{it} = h_{it}x_i + n_{it} \quad t = 1\ldots T, i = 1\ldots N_c \tag{1}$$

where $x_i$ is the transmitted signal, $n_{it}$ represents a complex noise with variance $\sigma_{it}^2$ and $h_{it}$ corresponds to the channel on receiver $t$ and tone $i$. The primal problem for power minimization of a $T$ -receiver $N_c$ parallel fading Gaussian broadcast channel with only common information subject to a minimum rate constraint for all receivers $R^{min}$ and a spectral mask constraint is

$$\begin{aligned}
&\min_{(\phi_i)_{i=1\ldots N_c}} \sum_{i=1}^{N_c} \phi_i \\
&\text{subject to} \sum_{i=1}^{N_c} log_2(1 + \frac{|h_{it}|^2 \phi_i}{\Gamma \sigma_{it}^2}) \geq R^{min} \quad \forall t \\
&\phi_i \leq \phi_i^{mask} \quad \forall i
\end{aligned} \tag{2}$$

with $\phi_i = E[|x_i|^2]$ the variance of the transmitted signal on channel $i$, $\phi_i^{mask}$ the mask constraint on sub-channel $i$, and $\Gamma$ the SNR gap which measures the loss with respect to theoretically optimum performance [29].

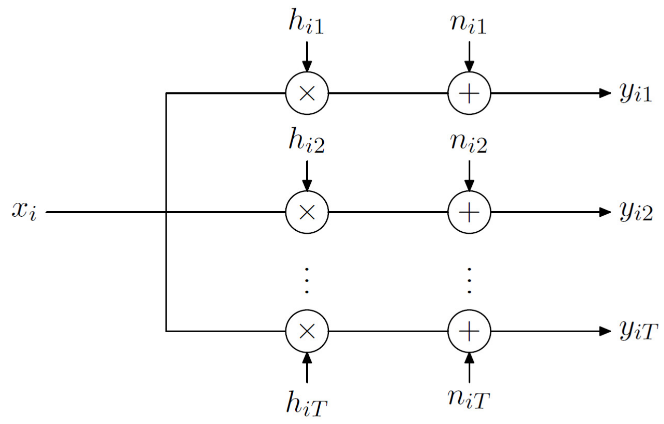


**Figure 7-5: $T$ -Receiver $N_c$ Parallel Fading Gaussian Broadcast Channel.**

The derivation of the modified Lagrangian function leads to a single variable search with $T$ Lagrange multipliers [30]. Therefore, the optimal power allocation has an infinite set of solutions, and the problem is intractable for $T > 1$. We propose a solution to this problem by defining a utility function which takes into account the possible achievable rates to the individual receivers. In the following, the weighted sum rate is chosen for this utility function as it allows us to consider the achievable rates to the receivers with a certain flexibility owing to the weighting parameters. Therefore, an inner loop determines the power allocation maximizing the weighted sum rate subject to a total power constraint and a spectral mask constraint for a fixed set of weights. The minimum rate is then selected amongst the possible achievable rates to the receivers. Then, an outer loop minimizes the power such that a minimum rate constraint is achieved. This process is repeated for all set of weights and the set of weights exhibiting the least power determines the power allocation for power minimization subject to a minimum rate constraint. The primal problem for weighted sum rate maximization subject to a power constraint $P^{tot}$ and a spectral mask constraint is:

$$\begin{aligned} &\max_{(\phi_i)_{i=1\ldots N_c}} \sum_{i=1}^{N_c}\sum_{t=1}^{T} w_t log_2 (1+\frac{|h_{it}|^2 \phi_i}{\Gamma \sigma_{it}^2}) \\ &\text{subject to} \sum_{i=1}^{N_c} \phi_i = P^{tot} \\ &\phi_i \le \phi_i^{mask} \quad \forall i \end{aligned} \tag{3}$$

with $\sum_{t=1}^{T} w_t = 1$. As the objective function is concave, the power allocation can be derived by the standard Karush-Kuhn-Tucker (KKT) condition [30]. By taking the derivative of the modified Lagrangian function with respect to $\phi_i$, we can solve the KKT system of the optimization problem. The derivative with respect to $\phi_i$ is given by

$$\frac{\partial L(\lambda,(\beta_i,\phi_i)_{i=1\ldots N_c})}{\partial \phi_i} = \frac{1}{ln2}\sum_{t=1}^{T} \frac{w_t}{\frac{\Gamma \sigma_{it}^2}{|h_{it}|^2} + \phi_i} - (\lambda + \beta_i) \tag{4}$$

with $\lambda$ the Lagrange multiplier associated with the total power constraint, and $\beta_i$ the Lagrange multipliers corresponding to the spectral mask constraint. Nulling the derivative gives

$$\frac{\partial L(\lambda,(\phi_i)_{i=1\ldots N_c})}{\partial \phi_i}=0 \Rightarrow \sum_{t=1}^{T}\frac{w_t}{\frac{\Gamma\sigma_{i1}^2}{|h_{it}|^2}+\phi_i}=\underbrace{\lambda ln2}_{\tilde{\lambda}}+\underbrace{\beta_i ln2}_{\tilde{\beta}_i} \tag{5}$$

From the previous formula, one can see that the power allocation depends on the number of receivers $T$. Let us derive the power allocation for different number of receivers:

- For a single receiver $T=1$, the power allocation corresponds to Gallager's water-filling strategy for single-user parallel Gaussian channels [28] with additional spectral mask constraint given by:

$$\frac{\partial L(\lambda,(\phi_i)_{i=1\ldots N_c})}{\partial \phi_i}=0 \Rightarrow \phi_i=\left[\frac{1}{\tilde{\lambda}+\tilde{\beta}_i}-\frac{\Gamma\sigma_{i1}^2}{|h_{i1}|^2}\right]^+ \tag{6}$$

- For two receivers $T=2$, the power allocation is a type of water-filling strategy given by the solution of a quadratic equation.

$$\begin{aligned}&\frac{\partial L(\lambda,(\beta_i,\phi_i)_{i=1\ldots N_c})}{\partial \phi_i}=0\\ &\Rightarrow \frac{w_1}{\underbrace{\frac{\Gamma\sigma_{i1}^2}{|h_{i1}|^2}}_{a_i}+\phi_i}+\frac{w_2}{\underbrace{\frac{\Gamma\sigma_{i2}^2}{|h_{i2}|^2}}_{b_i}+\phi_i}=\tilde{\lambda}+\tilde{\beta}_i\end{aligned} \tag{7}$$

The quadratic equation to be solved is

$$\begin{aligned}(\tilde{\lambda}+\tilde{\beta}_i)\phi_i^2+((\tilde{\lambda}+\tilde{\beta}_i)(a_i+b_i)-(w_1+w_2))\phi_i\\ +(\tilde{\lambda}+\tilde{\beta}_i)a_ib_i-(w_1b_i+w_2a_i)=0.\end{aligned} \tag{8}$$

The discriminant is given by

$$\begin{aligned}\Delta=(\tilde{\lambda}+\tilde{\beta}_i)^2(a_i-b_i)^2+(w_1+w_2)^2\\ -2(\tilde{\lambda}+\tilde{\beta}_i)(a_i-b_i)(w_1-w_2)\end{aligned}. \tag{9}$$

The power allocation is given by the positive root

$$\phi_i=\left[\frac{1}{2(\tilde{\lambda}+\tilde{\beta}_i)}+\sqrt{\frac{(w_1+w_2)^2}{4(\tilde{\lambda}+\tilde{\beta}_i)^2}-\frac{(a_i-b_i)(w_1-w_2)}{2(\tilde{\lambda}+\tilde{\beta}_i)}+\frac{(a_i-b_i)^2}{4}}-\frac{a_i+b_i}{2}\right]^+. \tag{10}$$

In this formula, the power allocation for weighted sum rate subject to a power constraint and a spectral mask constraint takes into account the difference between the water-fill functions and the weights of the different receivers.

- For three receivers $T = 3$ and four receivers $T = 4$, the power allocation is a type of water-filling strategy given by the solution of a cubic and a quadratic equation, respectively. Therefore, the power allocation can also be found analytically. (The solution is not given here due to space limitations.) With $T > 4$, the power allocation is given by the solution of a polynomial equation with degree $T$. In general, the roots cannot be expressed analytically but can be solved numerically.

The algorithm uses the weights to minimize the power subject to a minimum rate constraint and a spectral mask constraint. Algorithm 1 provides the power allocation for power minimization subject to a minimum rate constraint $R^{min}$ of a $T$-receiver $N_c$ parallel fading Gaussian broadcast channel with only common information ($\beta_i = 0 \quad \forall i$). The inner loop and the outer loop correspond to lines 13-21 and 8-29 respectively. To include a spectral mask constraint, we need to replace line 14 with the modifications given in Algorithm 2.

**Algorithm 1** Minimization of the power subject to a minimum rate constraint

1 n=0<br>
2 for all $w_1, \ldots, w_T$, with $\sum_{t=1}^{T} w_t = 1$<br>
3 n=n+1<br>
4 init $P = 10^{-9}$<br>
5 init $pstep = 2$<br>
6 init $p = 0$<br>
7 init $R_t = 0 \ \forall t$<br>
8 while $|min(R_1, \ldots, R_T) - R^{min}| > \epsilon$<br>
9 init $\lambda = 10^{-9}$<br>
10 init $step = 2$<br>
11 init $b = 0$<br>
12 init $\phi_i = 0 \ \forall i$<br>
13 while $| \sum_{i=1}^{N_c} \phi_i - P| > \epsilon$<br>
14 Calculate $\phi_i \ \forall i$ according to (4)'s root<br>
15 if $\sum_{i=1}^{N_c} \phi_i - P < 0$<br>
16 $b = b + 1$<br>
17 $\lambda = \lambda / step$<br>
18 $step = step - 1/2^b$<br>
19 end if<br>
20 $\lambda = \lambda * step$<br>
21 end while<br>
22 Individual rates $R_t = \sum_{i=1}^{N_c} \log_2(1 + \frac{|h_{it}|^2 \phi_i}{\Gamma \sigma_{it}^2}) \ \forall t$<br>
23 if $min(R_1, \ldots, R_T) - R^{min} > 0$<br>
24 $p = p + 1$<br>
25 $P = P / pstep$<br>
26 $pstep = pstep - 1/2^p$<br>
27 end if<br>
28 $P = P * pstep$<br>
29 end while<br>
30 $P_n = P$<br>
31 end for<br>
32 $P^{min} = min(P_n)$

**Algorithm 2** Modifications to **Algorithm 1** to take into account a spectral mask constraint

for $i = 1$ to $N_c$<br>
init $\beta = 10^{-9}$<br>
init $mstep = 2$<br>
init $m = 0$<br>
for $iteration = 1$ to 20<br>
Calculate $\phi_i$ according to (4)'s root<br>
if $\phi_i > \phi_i^{mask}$<br>
$\phi_i = \phi_i^{mask}$<br>
end if<br>
if $\phi_i - \phi_i^{mask} < 0$<br>
$m = m + 1$<br>
$\beta = \beta / mstep$<br>
$mstep = mstep - 1/2^m$<br>
end if<br>
$\beta = \beta * mstep$<br>
end for<br>
end for

#### 7.3.1.2 *Multiple tactical radio networks*

In this paragraph, we consider the scenario in which $N$ different cognitive radio networks cannot cooperate with each other and wish to broadcast a common information to their network by sharing the same $N_c$ parallel sub-channels. This scenario is particularly adapted to tactical radio networks in which $N$ different networks coexist in a given area and broadcast a common information (voice, data, etc.) to their group. With current technologies, if the legacy radios of the coalition nations share the same parallel sub-channels, the interference would increase and lead to an unsuccessful reception. Cognitive radio enables the adaptation of the transmission parameters (transmit power, carrier frequency, modulation strategy) to these scenarios. Based on the results of the preceding paragraph, we propose a completely autonomous distributed power allocation. Considering $N$ different networks and assuming that each network $j$ has $T_j$ receivers, the received data can be modeled as

$$y_{j,it} = h_{jj,it} x_{ji} + \sum_{k \neq j}^{N} h_{jk,it} x_{ki} + n_{j,it} \quad \begin{array}{l} i = 1 \ldots N_c, \\ j = 1 \ldots N, . \\ t = 1 \ldots T_j \end{array} \quad (11)$$

where $n_{j,it}$ represents a complex noise with variance $\sigma^2_{j,it}$ and $h_{jk,it}$ corresponds to the channel from network $k$ to $j$ on receiver $t$ and tone $i$. Similarly to paragraph 0 in which the initial problem of power minimization subject to minimum rate constraint is intractable for $T > 1$, we propose a way to solve the initial problem by defining an utility function (the weighted sum rate) which takes into account all the achievable rates of the receivers and to select the minimum rate in each network. The primal problem for the weighted sum rate maximization subject to a total power constraint and a spectral mask constraint per network (inner loop) is given by:

$$\begin{array}{l} \max\limits_{(\phi_{ij})_{i=1\ldots N_c}^{j=1\ldots N}} \sum_{i=1}^{N_c} \sum_{j=1}^{N} \sum_{t=1}^{T_j} w_{jt} log_2 \left(1 + \dfrac{|h_{jj,it}|^2 \phi_{ij}}{\Gamma(\sigma^2_{j,it} + \sum_{k \neq j} |h_{jk,it}|^2 \phi_{ik})}\right) \\ \text{subject to} \sum_{i=1}^{N_c} \phi_{ij} \leq P_j^{tot} \quad \forall j \\ \phi_{ij} \leq \phi_{ij}^{mask} \quad \forall i, j \end{array} \quad (12)$$

This problem is highly non-convex and no closed-from solution can be derived. Even if a centralized cognitive manager was able to collect all of the Channel State Information (CSI) within and between the different networks, it would require an exhaustive search over all possible $\phi_{ij}$ s, or a more efficient genetic algorithm. To solve this problem, we propose a sub-optimal distributed algorithm based on the iterative water-filling algorithm initially derived for dynamic spectrum management in Digital Subscriber Line (DSL) [25]. The iterative water-filling principle is extended to multiple cognitive tactical radio networks, in which each network considers the interference of the other networks as noise and performs water-filling on its parallel multicast channels. Each update of one network's water-filling affects the interference of the other networks. This process is repeated iteratively between the networks until the power allocation of all networks converges and reaches a Nash equilibrium. As the power updates between networks can be performed asynchronously, an iterative water-filling-based algorithm for the coexistence between multiple cognitive tactical radio networks may be considered. Let us derive the modified Lagrangian function:

$$L((\lambda_j)_{j=1\ldots N},(\beta_{ij},\phi_{ij})_{i=1\ldots N_c}^{j=1\ldots N}) = \sum_{i=1}^{N_c}\left(\sum_{j=1}^{N}\sum_{t=1}^{T_j} w_{jt} log_2(1+\frac{|h_{jj,it}|^2\phi_{ij}}{\Gamma(\sigma_{j,it}^2+\sum_{k\neq j}|h_{jk,it}|^2\phi_{ik})}) - \sum_{j=1}^{N}(\lambda_j+\beta_{ij})\phi_{ij}\right)$$
$$+\sum_{j=1}^{N}\lambda_j P_j^{tot} + \sum_{i=1}^{N_c}\sum_{j=1}^{N}\beta_{ij}\phi_{ij}^{mask} \tag{13}$$

in which the $\lambda_j$'s and $\beta_{ij}$'s are the Lagrange multipliers. We assume that each transmitter has the knowledge of the noise variances and the channel variations in its own network $j$

$$\begin{cases} \sigma_{j,it}^2+\sum_{k\neq j}|h_{jk,it}|^2\phi_{ik} & \forall i,\forall t \\ h_{jk,it} & k=j,\forall i,\forall t \end{cases} \tag{14}$$

This knowledge can be acquired through a feedback channel from the receivers to the transmitter of each network assuming that the acquisition time is much lower than the coherence time of the channel fading. To this end, each terminal must be equipped with a spectrum sensing function to estimate the noise variances and a channel estimation function to estimate its channel variations. Then, by taking the derivative of the modified Lagrangian function with respect to $\phi_{ij}$, we can solve the KKT system of the optimization problem:

$$\frac{\partial L((\lambda_j)_{j=1\ldots N},(\beta_{ij},\phi_{ij})_{i=1\ldots N_c}^{j=1\ldots N})}{\partial\phi_{ij}} =$$
$$\frac{1}{ln2}\sum_{t=1}^{T_j}\frac{w_{jt}}{\Gamma(\frac{\sigma_{j,it}^2}{|h_{it}|^2}+\sum_{k\neq j}\frac{|h_{jk,it}|^2}{|h_{it}|^2}\phi_{ik})+\phi_i} - (\lambda_j+\beta_{ij}) \tag{15}$$

For transmitter $j$, the power allocation is the solution given by the roots of (4) with the interference terms estimated at each receiver within the network $j$. For instance, with two receivers $T_j = 2$, the power allocation within the network $j$ is given by (10) with the following modifications:

$$\begin{cases} a_i = \Gamma(\sigma_{j,i1}^2+\sum_{k\neq j}|h_{jk,i1}|^2\phi_{ik}) \\ b_i = \Gamma(\sigma_{j,i2}^2+\sum_{k\neq j}|h_{jk,i2}|^2\phi_{ik}) \end{cases} \tag{16}$$

Therefore, a distributed power allocation of $N$ different networks can be obtained by updating iteratively the powers of the different transmitters using the single-transmitter power allocation for minimizing the power subject to a minimum rate constraint and a spectral mask constraint. However, in Algorithm 2, the weight loop encompasses the outer loop to find which set of weights corresponds to the global minimum power satisfying a minimum rate constraint $R^{min}$. As the algorithm should be distributed and autonomous, the set of weights minimizing the power has to be determined for each network independently. To this end, we have to move the weight loop inside the outer loop by introducing a rule based on the rates. An adequate rule is to introduce a deviation metric (DM) which measures the dispersion of the rates. The DM must be computed within each network $j$ for each set of weights $n$ over the $T_j$ receivers. The rule is given by the following formula:

$$DM_j(n) = \frac{\sqrt{T_j \sum_{t=1}^{T_j} [(R_{jt}(n) - \frac{1}{T_j} \sum_{t=1}^{T_j} R_{jt}(n))^2]}}{\sum_{t=1}^{T_j} R_{jt}(n)} \quad (17)$$

with $R_{jt}(n)$ the rate for the network $j$, receiver $t$ and the set of weights $n$. This rule allows us to achieve the global minimum power although the decision has to be taken inside the outer loop. It basically means that for a given power the closer the rates of the different receivers within a network, the less power will be needed to achieve the minimum rate constraint. This algorithm is referred to as Algorithm 3 in the simulation results.

*7.3.1.3 Simulation results*

In the first set of simulations, we compare the algorithm for a single tactical radio network with the trivial case in which the water-filling is performed on the receiver with the worst channel conditions, i.e. the worst receiver strategy. Note that the worst receiver strategy can be seen as a special case of the presented algorithm in which $w_t = 0 \ \forall t$ except for the worst receiver. The log-distance path loss model is used to measure the path loss between the transmitter and the receivers [31], with bandwidth $\Delta f = 25$ kHz, $N_c = 4$ sub-channels, carrier frequency $f_c = 80$ MHz, path loss exponent $n = 4$, reference distance $d_0 = 20$ meters and thermal noise $\sigma_n^2 = 10^{-16}$. For the simulations, we use a square area of $1 \text{ km}^2$ in which the transmitter and $T = 2$ receivers are placed randomly using Monte Carlo trials. The SNR gap for an uncoded Quadrature Amplitude Modulation (QAM) to operate at a symbol error rate $10^{-7}$ is $\Gamma = 9.8$ dB. The scenario considers a very strong noise ($\sigma_n^2 = 10^{-9}$) seen on the $4^{th}$ sub-channel by the first receiver and on the $1^{st}$ sub-channel by the second receiver. The different noises seen by the different receivers can be thought of as sub-channel variations depending on the location, a sub-channel occupied by a primary or a secondary transmitter, a jammer, etc.

The left part of Figure 7-6 shows the results of the power minimization subject to a minimum rate constraint per receiver ranging from $R^{min} = 2$ kbps to $R^{min} = 512$ kbps over $10^3$ Monte Carlo trials for the locations of the transmitter and the receivers. Algorithm 1 provides a substantial gain compared to the worst receiver strategy. The right part of Figure 7-6 shows that the algorithm converges within 30 iterations (the number of iterations for convergence mainly depends on the starting point, in this case $P = 10^{-11}$). Since it is based on closed-form expressions, the algorithm has reasonable complexity for a low number of receivers as the search for the best set of weights requires an exhaustive search over all possible weights.

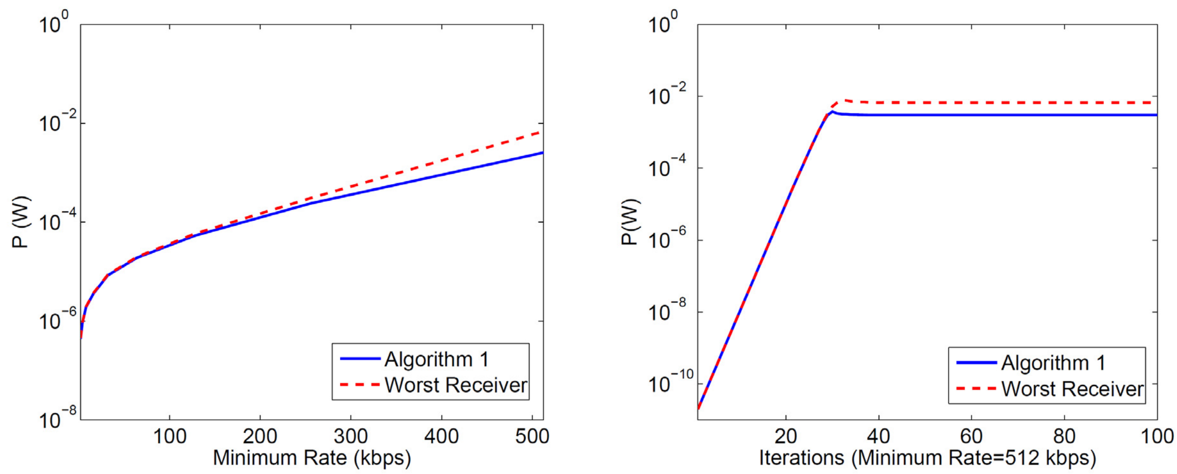


**Figure 7-6: Results on the Power Minimization Subject to a Minimum Rate Constraint for a Single Tactical Radio Network.**

In the second set of simulations, we compare the iterative water-filling-based algorithm developed in paragraph 0 for $N$ networks with the worst receiver strategy extended to multiple networks. Simulation results are performed with $N = 2$ networks, $T_j = 2$ receivers $\forall j$ and $N_c = 4$ sub-channels. We consider a scenario in which all receivers see a different noise $\sigma_n^2$ on their $N_c = 4$ sub-channels (similar to the first set of simulations). In the first network, a very strong noise ($\sigma_n^2 = 10^{-9}$) is seen on the $4^{th}$ sub-channel by the first receiver and on the $1^{st}$ sub-channel by the second receiver. In the second network, a very strong noise ($\sigma_n^2 = 10^{-9}$) is seen on the 3$^{rd}$ sub-channel by the first receiver and the $2^{nd}$ sub-channel by the second receiver. The left part of Figure 7-7 shows the results of the power minimization subject to a minimum rate constraint ranging from $R^{min} = 2$ kbps to $R^{min} = 512$ kbps over $10^3$ Monte Carlo trials for the locations of the transmitter and the receivers. In this case, Algorithm 3 is the only strategy which provides a viable solution because the worst receiver strategy tends to utilize the maximum available power of 1 Watt. The right part of Figure 7-7 shows that the Deviation Metric (DM) reduces as the algorithm converges. It can be seen that in practical scenarios in which the interference temperature varies along the sub-channel and the receiver locations, Algorithm 3 provides an efficient distributed strategy to find the power allocation of multiple networks in which each transmitter has to broadcast common information to its receivers.

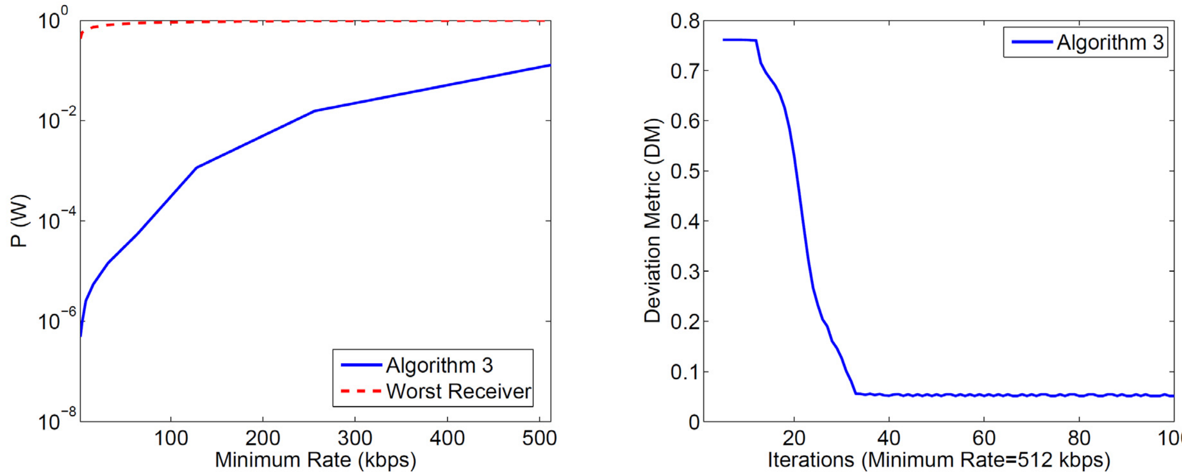


**Figure 7-7: Results on the Averaged Power Minimization Subject to a Minimum Rate Constraint Averaged for the Coexistence of Two Tactical Radio Networks.**

The last simulation results (Figure 7-8 and Figure 7-9) show the behavior of the algorithm in a realistic scenario in which a network is moving toward a second network. This software realized in Matlab demonstrates that each network tends to utilize most of the sub-channels when the networks are far apart (weak interference). However, when the network are close to each other (strong interference), the algorithm converges toward an FDMA solution in which the networks do not interfere at all. Moreover, when a jammer is present, both networks avoid the jammed sub-channel.

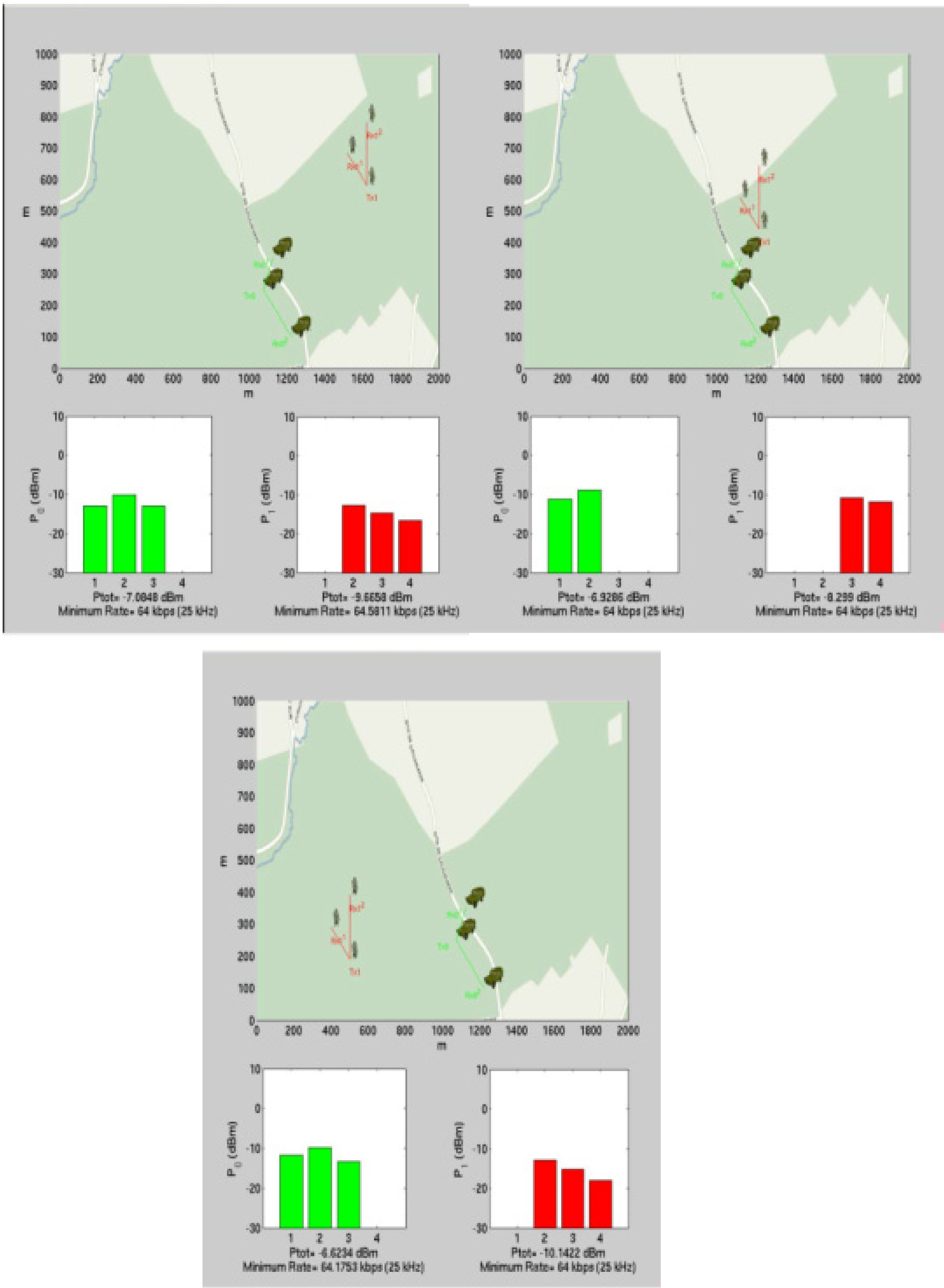


**Figure 7-8: Simulation Results with the Matlab Software.**

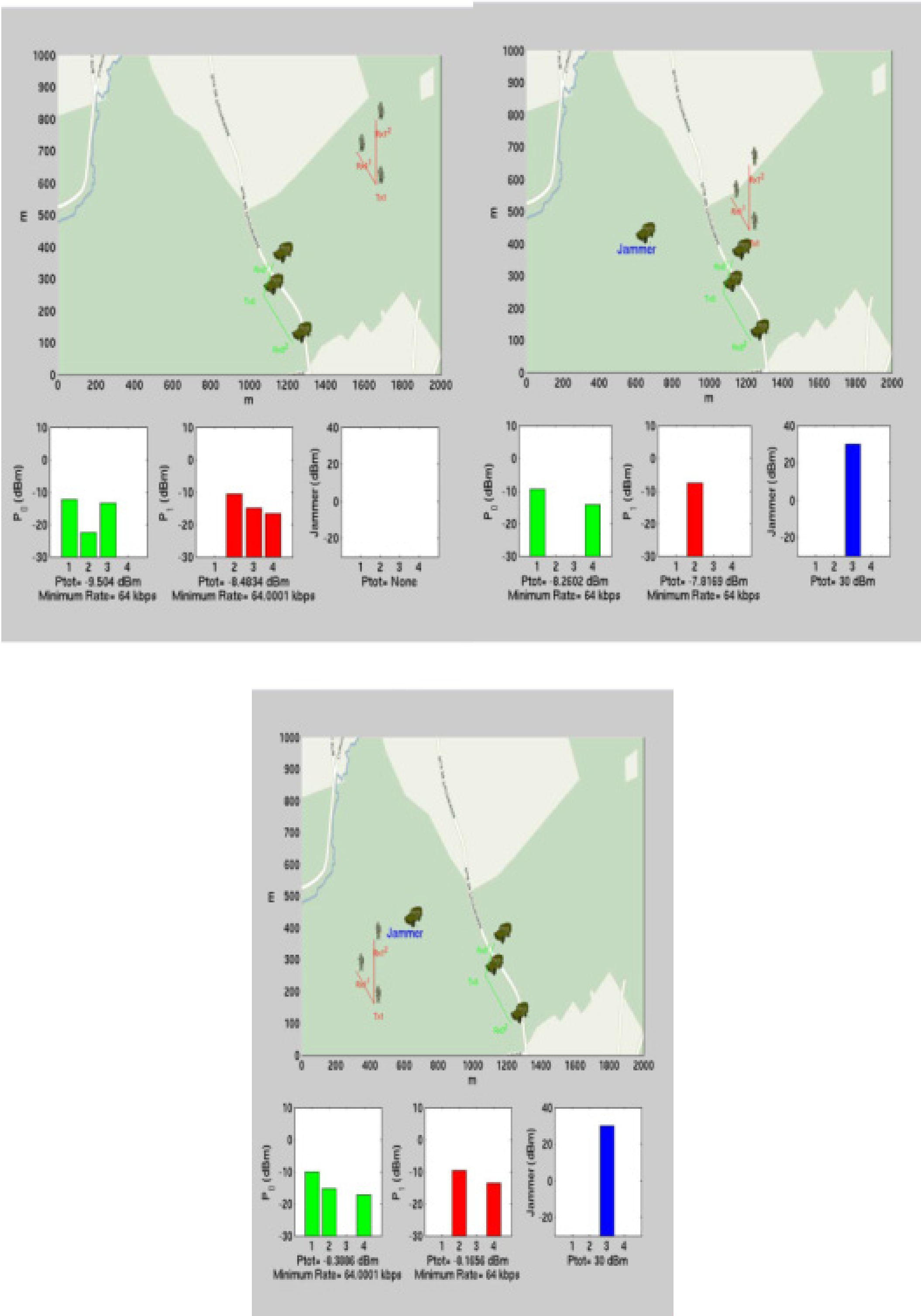


**Figure7-9: Simulation Results of a Jammer with the Matlab Software.**

### 7.3.2 On Spectrum Sharing in Autonomous and Coordinated Dynamic Spectrum Access Systems: A Case Study

This section is a brief summary from the paper with the same title, by Tore Ulversøy, Torleiv Maseng and Jørn Kårstad. (The full paper is available from http://ieeexplore.ieee.org).

#### *7.3.2.1 Introduction*

A comparison is here made of the ‘competitive optimum’ (CO), being the converged result of the Iterative Water Filling (IWF) [32][33][34] algorithm, with the Global Optimum (GO), for illustrative deployments of two radio links and two available spectrum segments. Two different cases for the IWF are studied. In one, aggressive behavior, in which the links try to apply power to maximize their own data rate within their power limitations, is defined. In the other, we assume that some ‘intelligent agent’ has provided the radio link with an optimum target rate that the IWF of the link tries to reach. Suggestions for how to improve from the CO in the cases where the deviations are large are also provided.

#### *7.3.2.2 Background: DSA Architectures and Sharing Principles*

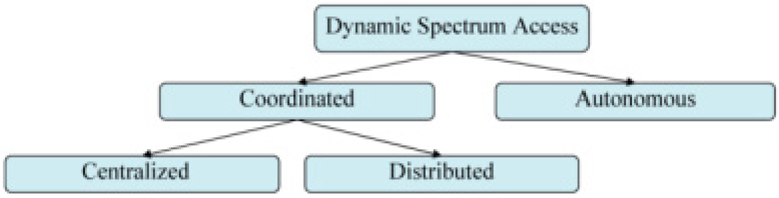


**Figure 7-10: A Classification of DSA Architectural Concepts.**

A suggested classification of DSA architectural concepts, in an idealized form, is provided in Figure 7-10. The autonomous model is characterized with no coordination between the spectrum-using entities, the entities are only aware of the sensed spectrum and their transmitted power density. In the distributed (or decentralized) model, additionally the entities coordinate with nearby peer nodes. In the (idealized) centralized model, each spectrum consuming entity coordinates with a central broker which has ideally updated and global knowledge and makes ideal spectrum decisions.

Further, in the following the ‘Open Sharing’ spectrum sharing model is assumed, in which the spectrum is shared between users which all have equal rights for using the spectrum [35].

### *7.3.2.3 Mathematical model*

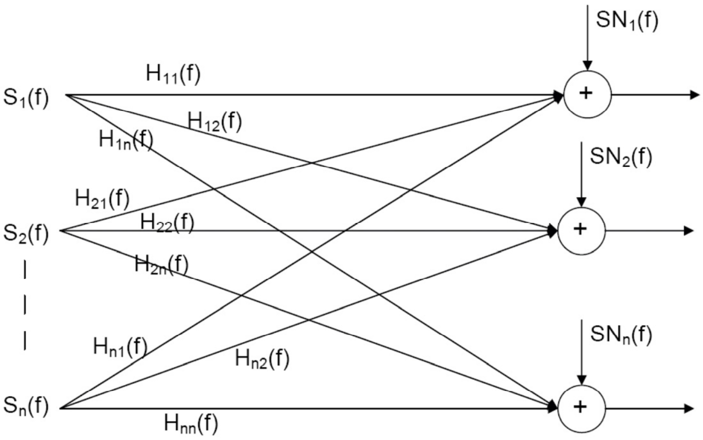


**Figure 7-11: The N-Link Interference Model.**

The analysis is based on a model where there are n transmitters and receivers, and where neither transmitters no receivers cooperate [33], and may be viewed as n interfering links, see Figure 7-11.

The spectrum band that is being shared between the links has a width B and is in general divided into M segments. For this particular case study, both n and M are set equal to two, i.e. the simple case of only two links and two segments are analyzed in order to easily interpret the results.

Also for reasons of simplicity, we use the sum of bit rates over the links as the function that we want to maximize, and use the Shannon capacity expression with a signal-to-noise compensation factor Γ to account for a difference between theoretical and practical rates [32] to calculate link rates:

$$Rsum = \sum_{i=1}^{n} \Delta f \sum_{k=0}^{M-1} log_2\left(1 + \frac{S_i(f_k)}{N_i(f_k) + \sum_{j \neq i} \alpha_{ji} S_j(f_k)}\right)$$

where

$$\alpha_{ji}(f_k) = \frac{\Gamma \cdot |H_{ji}(f_k)|^2}{|H_{ii}(f_k)|^2}$$

and

$$\alpha_{ji}(f_k) = \frac{\Gamma \cdot |H_{ji}(f_k)|^2}{|H_{ii}(f_k)|^2}$$

and where $S_i(f_k)$ is the (two-sided) power spectrum density of link I in segment k, which is subject to a power restriction of link i, $P_i$.

We define the Global Optimum (GO) as the maximum $Rsum$ point in the general case where all the $S_i$ may be varied within their link power restrictions. Finding the GO requires a complete knowledge of all the link gains and power restrictions, something that requires coordination and is best accomplished in the centralized architectural model. However, the general $Rsum$ expression is a non-convex function, and hence in the general case cannot be solved by convex optimization and thus it has 'prohibitively high' [32] computational complexity. Here, for the very limited number of links and segments, we use a brute-force search to find the GO solution.

The optimum $R_i$ when assuming that the power density assignments of all other links $j \neq i$ are constant, is, however, a convex function and the optimum point may in this case be found by the method of Lagrange multipliers, the result being the well-known water-filling solution [32][33][34], which for each k and i is

$$S_i(f_k) = \begin{cases} L_i - \left[N_i(f_k) + \sum_{j \neq i} \alpha_{ji} S_j(f_k)\right] & if \left[N_i(f_k) + \sum_{j \neq i} \alpha_{ji} S_j(f_k)\right] \leq L_i \\ 0 & otherwise \end{cases}$$

The converged $R_{sum}$ solution when applying the IWF in each of the links is termed the Competitive Optimum (CO), and is a well-known approximation to the GO. Assuming that the interference from the other links may be assessed by measurements, this solution may be found by using local information in each link only, and hence may be used also for autonomous links.

The IWF is intended to work with target rates within 'permissible regions' [32] or optimum *a priori* calculated target rates [33]. Such optimum *a priori* targets require that some kind of centralized agent, having knowledge of the links in the area, does an *a priori* calculation. This, however, is a non-autonomous operation. Here, we investigate both the case that such optimum *a priori* rates are available, and as a second alternative that they are not available and that instead aggressive (very high) target rates are used.

#### *7.3.2.4 Case Study*

In this section, we study in detail some simple illustrative deployment examples in which there are only two interfering links, and the spectrum band consists of only two segments. The deployments are made and the link parameters calculated in the Norwegian FEFAS communications planning tool. A background noise level of -153dBm/Hz is assumed, a width of the spectrum band B of 50kHz, a centre frequency of 150 MHz, a maximum power of the transmitter of 1W and a Γ of 10dB (which will be a conservative value in many cases). For the CO solution, both aggressive and optimum target rates are used for the IWF algorithm. The optimum *a priori* rates are taken from the corresponding GO solution, while the aggressive target rates are set much higher than achievable rates.

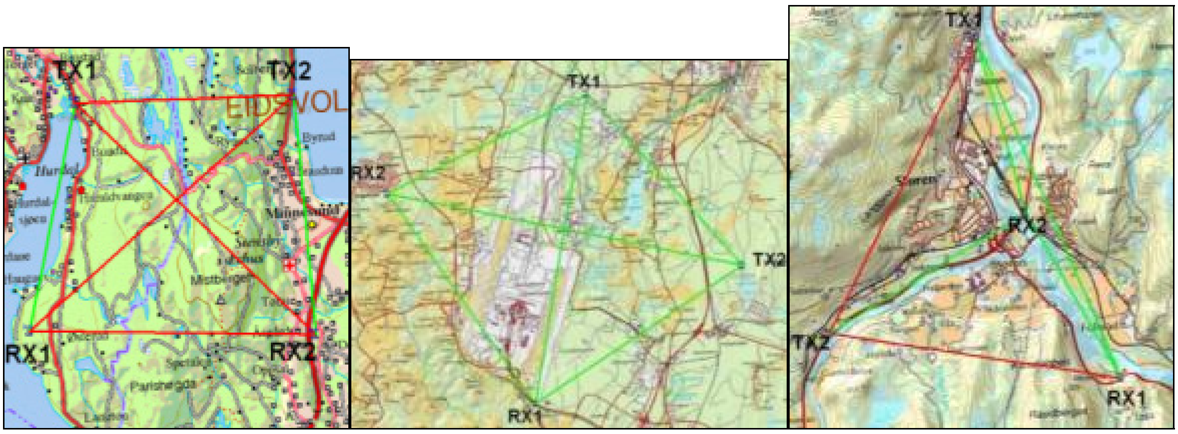


**Figure 7-12: Three Different Deployments of Two Simplex Radio Links: To the Left, a Low Interference Deployment, in the Middle a High Interference Deployment and to the Right an Unsymmetrical Interference Deployment (see explanation in the text).**

In the first of the three different deployments, to the left in Figure 7-12, the two links are deployed on each side of a ridge, such that the mutual interference is very low. In this case, the CO solution turns out to be identical to the GO one, see Figure 7-13 and both for optimum and aggressive target rates, which is logical since the interference term in the $R_{sum}$ expression is close to zero. Both links use both segments.

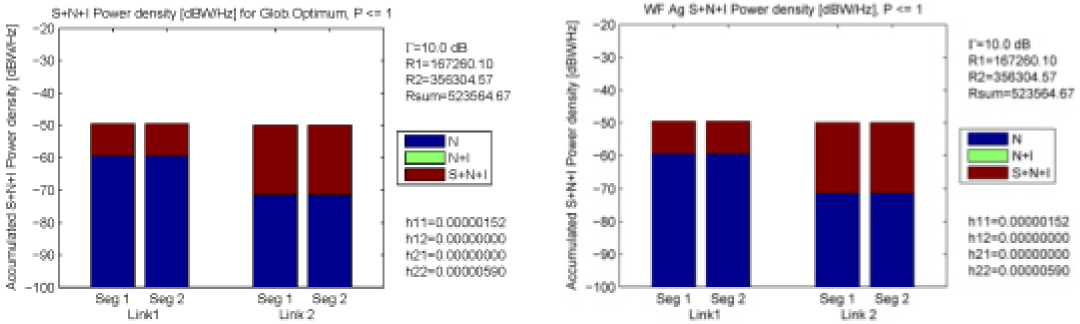


**Figure 7-13: Low Interference Case, GO Solution (left) and CO Solution (right).**

In the second deployment, in the middle of Figure 7-12, the two links are deployed across an airport, i.e. a flat landscape, and the communication paths are longer than the interference paths, giving high interference. In this case, in the GO solution, each link uses one segment, and good bit rates result. The CO solution on the other hand, both with aggressive and optimum target rates, causes very low bitrates (breakdown) of both links.

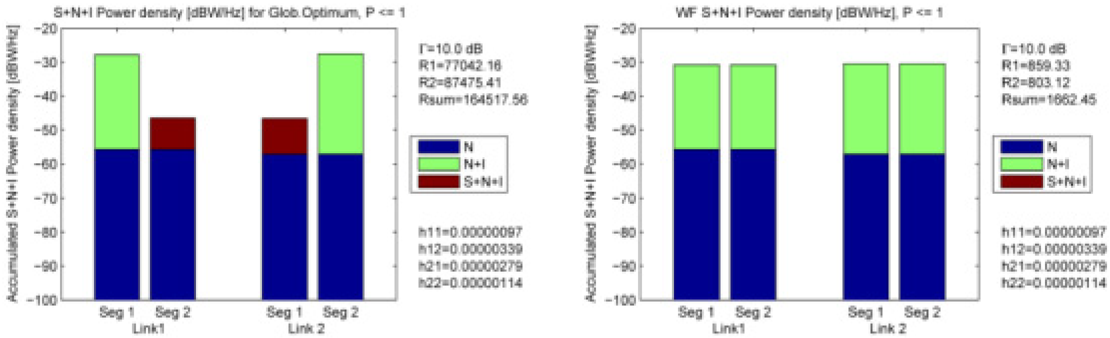


**Figure 7-14: High Interference Case, GO Solution (left) and CO Solution (right).**

The third deployment has a situation where the interference is not symmetric: Link 2 sees high interference levels from link 1. The receiver of link 1, on the other hand, is in the shadow of a mountain area relative to the transmitter of link 2, and sees very low interference. Here, in the GO solution, link 2, which has the shortest path and the best signal-to-noise ratio, gets to use both segments. In the CO solution with aggressive target rates on the other hand, both links use both segments and the performance of link 2 is destroyed by interference. Notably the CO solution using optimum target rates, though, result in the same results as the GO solution.

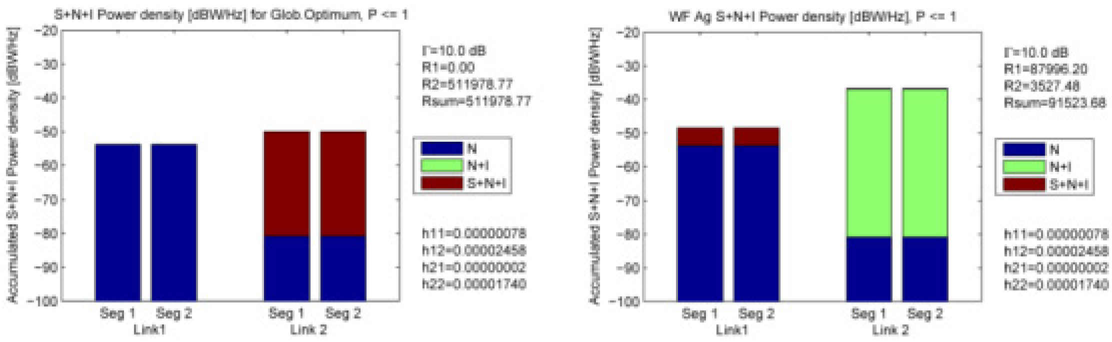


**Figure 7-15: Unsymmetric Interference Case, GO Solution (left) and CO Solution with Aggressive Target Rates (right). CO with Optimum Target Rates Give the GO Solution (same as on the left).**

In the two last deployments, strangulation (0 or low capacity) of individual links was observed. The paper further contains a discussion of means for how to avoid such strangulation (omitted here for brevity).

#### *7.3.2.5 Conclusions*

We have investigated and compared a Competitive Optimum (CO) power spectrum assignment and resulting calculated data rates to that of Global Optimum (GO) results, for a system of two radio links sharing two spectrum segments. The CO solution represents running the iterative water-filling algorithm with autonomous radio links. The GO solution represents what would be found by a centralized broker having complete knowledge of the links and having ideal calculation capabilities. Two different target rates for the IWF have been investigated, one being a high, aggressive target, the other one being an optimum target rate as calculated by an ideal centralized calculation entity. The comparison has been done for three different link deployments, with low, high and unsymmetrical interference.

For the low interference case, the CO solution is identical to the GO one, both with aggressive and optimum target rates. With the high-interference case, very low rates resulted with the CO solution relative to the GO, both for aggressive and optimum target rates. In the unsymmetric case, correct optimal *a priori* target rates lead to the CO solution being identical to the GO one, while aggressive target rates gave a less optimum CO solution.

A suggested policy for reducing the risk of very suboptimal rates for individual links, when each link runs the IWF for power spectrum assignment, is to limit the maximum number of segments that each link is allowed to use, thereby increasing the probability for other links to have acceptable communication rates in unsymmetric or high interference deployment cases.

### 7.3.3 A Comparison of Centralized, Peer-to-Peer and Autonomous Dynamic Spectrum Access in a Tactical Scenario

This section is a summary from the paper with the same title, by Tore Ulversøy, Torleiv Maseng, Toan Hoang and Jørn Kårstad. (The full paper is available from http://ieeexplore.ieee.org).

#### *7.3.3.1 Introduction*

A comparison is made of spectrum decisions, computational complexity, coordination traffic and behavior in hostile environments for the three basic DSA architectures: autonomous, peer-to-peer decentralized and centralized. The comparison is based on simulation results from using a 'link model' and modified Shannon link capacities. Further, autonomous policies and distributed interaction algorithms, based on additions/modifications to the iterative water-filling [32][33][34] algorithm, are suggested and simulated.

#### *7.3.3.2 Background: Architectures and Mathematical Model*

We refer to the same idealized architectures (autonomous, distributed and centralized) and the same link interference model as in 3.1.2. In the case here, the number of links n and the number of segments M are settable parameters in the calculation model. A Γ value of 10 is used in the simulations.

#### *7.3.3.3 Spectrum Decisions*

Simulations are carried out in MATLAB using a total of 5 different randomly selected scenarios, each with 20 links. The available spectrum band of size B is divided into M available segments. The scenarios are 20 by 20 km, and the link distances are uniformly distributed between 0 and 3.5km. (Further details of the parameters of the simulation are omitted here for brevity, but may be found in the paper).

We make the assumption that we want to maximize the sum bit rates over all the links in the scenario, but at the same time we want each link to maintain a minimum rate, Rmin.

For the autonomous architecture, and based on the ordinary IWF algorithm, we define three different policies to better maintain such a minimum rate:

- A1: Each link, instead of using a high target rate (i.e. using all its transmission power), uses a predefined target rate.
- A2: Each link, instead of being allowed to use all segments, has a maximum limitation on the number of segments it may use.
- A3: Same as A2, but each link's transmission power is reduced proportionally to the reduction in segments.

The better-performing of these policies, evaluated in the simulation model above, turned out to be the A2. A plot of the % of operational links, at three different values of Rmin, together with the average bit rate over all the links, is provided in Figure 7-16.

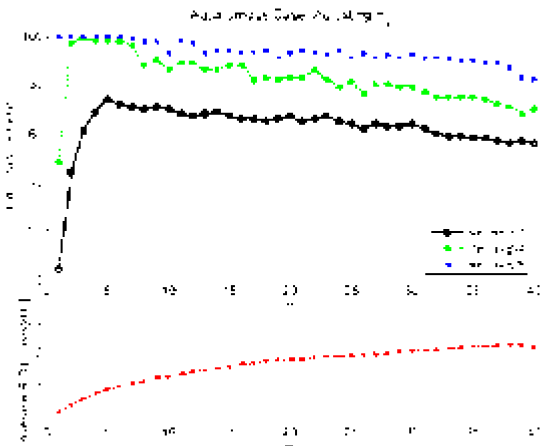

**Figure 7-16: Average % of Operational Links and Average Bits/s/Hz for the A2 Policy Averaged Over the 5 20 Link Scenarios.**

For the distributed architecture, two distributed interaction algorithms, again based on the IWF, are formulated:

- D1: In case a link does not reach its Rmin, it increases its own number of segments used and broadcasts a request for others within a coordination distance to lower their use (detailed conditions in the paper).

- D2: Same as D1 but increasing / reducing both the number of segments and also the target bit rate.

Results of running D2, expressed as a function of the coordination distance, is provided in Figure 7-17:

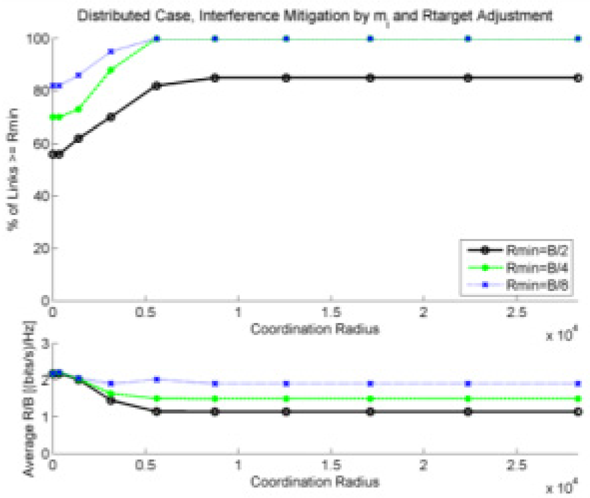


**Figure 7-17: D2: % Operational Links (top) and Average Bits/s/Hz (bottom) Averaged Over the 5 20 Link Scenarios.**

A comparison when requiring the links to be operational at Rmin=B/8 shows that the distributed interaction algorithms provide higher average bit rates compared to the autonomous policies.

For the centralized architecture, optimum power density allocation has very high computational complexity. An alternative is running D1 or D2 in the centralized broker instead of running it distributed, or using simpler, suboptimal algorithms.

#### *7.3.3.4 Computational Complexity, Coordination Traffic, DSA in Hostile Environment*

For the discussion of computational complexity, coordination traffic and issues in hostile environments, reference is made to the full paper [38].

#### *7.3.3.5 Conclusions*

Centralized, distributed and autonomous DSA have been compared in terms of spectrum decisions, computational complexity, coordination traffic and issues in a military, hostile environment. Three different autonomous spectrum decision policies and two distributed interaction algorithms, all built on the IWF algorithm as a basis, have been simulated. When requiring all links to meet the same minimum rate, the distributed interaction provided a higher average rate over all the links.

## 7.4 ARCHITECTURE AND PROTOCOLS

Cognitive features described in this document should ideally be implemented in all receivers and transmitters in the network. Of course, all transmitters in an area will not be part of the network and these will be modeled as generators of background noise. The receivers not part of the network may be disturbed unless their existence and their technical features [60] (location, antenna feature, frequency band of reception, noise figure, etc) are not available to the cognitive system through a database. In order to collect knowledge about the widely disturbed participants in the cognitive radio network, a model for the exchange of information is needed.

### 7.4.1 Centralized or Distributed

A number of models have been described for this dynamic sharing, including open sharing [41] also referred to as horizontal sharing [40] and hierarchical access [41] (vertical sharing [40]). Several architectural solutions have been described ranging from centralized solutions [42], [43], [44], [45], those with various forms of distributed interaction and through to autonomous spectrum sensing and ’etiquette’ based solutions. Centralized solutions may provide excellent interference supervision and hence superior Quality-of-Service (QoS) guarantees for the spectrum users, but this is at the expense of a high computational workload and the cost of the dedicated central infrastructure. The autonomous spectrum sensing and ’etiquette’ based solutions avoid such infrastructure requirements and may, with well defined ’etiquettes’, provide reasonable QoS and fairness in spectrum sharing. Still, as viewed from a license holder’s perspective, there are potential weaknesses in the protection of licensed systems and the QoS might not be sufficient for certain services [40]. Additionally, regulators, and also spectrum owners, may want to have higher levels of direct control. Having mutual coordination through some type of administrative communication channel [40] this should increase the QoS in Dynamic Spectrum Access (DSA). Since the coordination also extends to spectrum owner entities or central databases, this additionally increases the spectrum owner’s trust in the solutions.

### 7.4.2 Dedicated Control Channel

A recent example of such a coordination requirement is from the US spectrum regulator, FCC, in the ’Second Report and Order and Memorandum Opinion and Order’ in the Matter of ’Unlicensed Operation in the TV Broadcast Bands’[46]. This requires that all devices (except some personal/portable ones) to include provisions for Internet access to a database of both protected radio services and channels in use by unlicensed devices. A response to this report is a database proposal [47]. FCC has stated that it will not allow end-user equipments of ’White Spaces’ before such database is in place. The SDR Forum, now Wireless Innovation Forum, is also working on specifications for a third party database, Cognitive Radio Database (CRDB). This work is carried out by the cognitive radio Work Group [48]. A number of solutions for such coordinated communication between radio equipment have been defined. The common spectrum coordination channel (CSCC) [49] is a protocol consisting of a standardized CSCC-PHY and CSCC-MAC layer as well as a policy module. It is designed for efficient coordination of radio communication devices in unlicensed bands. The results showed improved throughput and delay for the tested devices (802.11 and Bluetooth), but a global predefined narrow-band sub-channel at the edge of the band is required for such communication. In the DIMSUMNet [43] which is a centralized concept, fixed frequencies are reserved as SPectrum Information (SPI) channels. The DSAP concept [42] [50] defines a protocol with detailed coordination messages. DSAP uses a dedicated channel for communication between the source and destination nodes. The Cognitive Pilot Channel (CPC) is described [51] as a coordination channel that is either ’out-band’, using dedicated frequencies outside the traffic channel frequencies, or ’in-band’, using specific channels of existing access technologies. It provides the entire spectrum information in the channel, but it is not explained how the spectrum information is acquired. Dedicated control channels have also been proposed in the DARPA XG program[40]. Another approach is coordination by beacons [40]. Coordination of entities through Internet connections where available has also been described in many concepts [43],[45]. The IEEE 1900.4 standardization group has started to define a DSA architecture. The parameters needed to be exchanged between various mobile systems have been defined.

### 7.4.3 Coordination Channel: MAC or Internet

The coordination may be carried out at the MAC channel like the “Automatic Link Establishment” (ALE) protocols used for HF transceivers. This is an elegant solution if it is possible to change the MAC layers of all receivers and transceivers. This solution is dependent of a major redesign of the terminals.

Assuming that there are many existing terminals that need to be brought into the network, it is quicker to implement the coordination software at the application level by running client software at operating system of the terminal and by assuming that all terminals are at one stage connected on the Internet.

### 7.4.4 The Frequency Resource Protocol (FRP)

To accomplish this task, the Frequency Resource Protocol (FRP) [65],[66] has been proposed. The frequency resource protocol will carry out spectrum coordinating from knowledge collected through an overlay network consisting of clients that are all connected at one time to the Internet. Each client maintains a database containing radio parameters (transmit power, receiver noise levels, antenna parameters, frequency bands, location and services required) for its own location and for all other clients within its frequency coordination range. Through the overlay network it will continuously attempt to update its database. Access to the overlay network will be limited for some clients to a planning period prior to the operation of passive receiver, private networks, wireless microphone clients, etc. Other clients will be connected continuously. Additionally, clients must also have knowledge of their geographic location. This information could be acquired from a GPS device or entered manually.

When using FRP, no common control channel is necessary. The coordination between the radio terminals (transmitters and receivers) is done via an Internet connection which may be provided via a PC that is not hard-wired to any radio or to a radio terminal which is only connected to the Internet once, or to a radio terminal continuously connected to Internet. The FRP-enabled client is downloaded from a central server run by an operator who is in the business of selling frequencies. In order to get access to the central server, the client must go through an authorization procedure which gives the operator confidence in the customer who is to run the client on the customer's platform. The purpose of running an FRP-enabled client and maintaining a database is to enable the user to make claims. A claim is the use of a frequency band for reception or transmission. Clients who already have access to a spectrum are able to claim additional frequencies for their own usage by using the FRP client. When using multimedia services like video on-demand, this requires more bandwidth than is available in the existing spectrum. An FRP-enabled client may be a software package installed on a computer as well as a software client installed in a radio unit. By using the FRP-enabled client, users may also claim frequency leases on behalf of radio devices which do not meet the requirements for using the FRP client (Internet connection, able to install software or knowledge of its geo-location). After some time, the client will have exchanged radio parameters with other clients thus retaining relevant information for its location. Even if this information keeps on changing for a while, the changes will eventually be fewer. The negotiating client may calculate a claim. This algorithm will only determine the transmitter power of the client, while considering the joint system optimization criteria. The claim contains frequency, location and duration. The calculation can be based on a robust non-selfish waterfilling algorithm or others [61][62][63][64][66].

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# Chapter 8 – SIMULATION METHODOLOGIES

## 8.1 INTRODUCTION

As seen in the previous sections, there are many ideas and analyses proposed about the theoretical gains of cognitive radio networks, but there is very little work available addressing the actual expected gains of different approaches. In particular, most work focuses on a single cognitive radio network, but when the spectrum is congested, the actions of one radio network affect neighbouring users within interference range. Furthermore, changing the spectrum access strategy may require certain additional overhead costs and the associated benefits need to be quantified.

The RTG has worked toward a simulation methodology proposal which focuses on the interaction of different networks, which may be owned by different members of the coalition, rather than the internal characteristics of each network. This work will be continued in the subsequent RTG on cognitive radio.

The simulation methodology is expected to support investigations of the overall gains of certain features of cognitive radio networks relative to legacy approaches, and to identify which cognitive radio strategies offer the greatest benefits and least disruptions to other users.

The approach proposed is based on mission vignettes, such as those developed elsewhere within NATO NC3A, which provide a context for the radio operating conditions and user demands.

## 8.2 SIMULATION CONCEPT

### 8.2.1 Vignette

The vignette, which is described in Chapter 9, defines the operating environment, the participants, i.e. the users of the spectrum and their locations. The geographical description provides the distances between user networks, from which interference characteristics can be computed. In a more complex implementation, the topography of the environment might be incorporated into the propagation conditions, but at this point only the distances are used. Randomness is introduced through the propagation models. Additional information regarding each user group can be extracted from, or defined within, the vignette, depending on the complexity of the simulation.

Additional context is required that is not specified within the original vignette definitions, in particular the spectrum resources. The number of VHF and UHF channels available is defined – this parameter can be varied to make the operating conditions more challenging.

### 8.2.2 Missions

The term “mission” is used to describe a set of services that are required by each user group. These consist of combinations of voice, data and video as described in Section 8.5. For each mission, the simulation is implemented to evaluate whether the required services can be supported. Randomness in introduced through variability in the demand for those services. Different missions, with increasing spectrum requirements, can be defined to stretch the capabilities of the system to support the services.

### 8.2.3 Clouds

The objective is to model the impact of interference between networks, rather than to model the internal structure of the networks themselves. The aim of the work is to investigate the issues with “dynamic coordination of radio networks”. Each network may belong to a different nation, have different numbers of nodes, and be produced by different manufacturers to different standards and protocols.

The "cloud" is an abstraction of the network which provides the basis to evaluate the interference effects and effect of dynamism within the scenario. There are several possible parameters to define the clouds at the abstracted level: these include size, number of nodes, number of frequency channels, mobility, and propagation environment. To minimize the simulation complexity, only a high-level description of the cloud as it appears to an external observer is required: the location, the power emitted, the channels used, the SINR as a general performance metric (see Section 8.6) and the types of services supported (see Section 8.5).

## 8.3 OPERATING ENVIRONNENT

The characteristics of the clouds depend on the context and environment of each. The following parameters are important to describe a cloud and to evaluate the influence of a cloud on another cloud.

- **Transmit power**: The maximum power and the actual transmit power for the channels in each frequency band (VHF, UHF) determine the dimensions of the cloud.
- **Number & bandwidth of channels**: Channels in the VHF band are 25 kHz bandwidth. In the UHF band channel bandwidth is 1 MHz. The number of channels is a variable in the simulations: fewer channels stress the system more.
- **Location**: Cloud centres are given by the vignette (see Chapter 9) Only one value is taken into account to characterize the interference, which could be, for example, the worst-case interference in the cloud.
- **Propagation characteristics**: Clouds representing networks of coherently moving nodes, such as convoys, are modelled as having fixed distances between the nodes and LOS propagation. In more complex environments, the nodes also have a fixed separation, but propagation between nodes is assumed to be NLOS hence the path loss is randomly selected for each simulation realisation. The propagations characteristics between clouds are determined also by their mobility (fixed, mobile) and by their LOS component. The path losses between the channels of the clouds are also randomly selected for each simulation realisation in the case of NLOS. There could be shadowing effects between clouds. The shape of the clouds are determined by the antenna pattern (omnidirectional, directional) and by the antenna height.

## 8.4 MISSIONS

The proposed simulation methodology aims at evaluating the CR system performance by assessing its capability to support operational missions. For a given mission, the communication needs are expressed in terms of services that the communication system must successfully support. We consider here communication services used during missions, such as Push-To-Talk (PTT) and Blue-Force-Tracking (BFT), that are detailed in Section 8.5.

Each cloud derived from a vignette is associated to a set of services that is relevant for its mission. Consequently, missions consist of combinations of services. The following table gives some example of services attached to two different missions in the case of a two cloud vignette.

**Table 8-1: Example of Services Attached to 2 Different Missions.**

| | Cloud #1 | | | | | | Cloud #2 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Services | PTT | BFT | C2 | VN | Data | RTV | PTT | BFT | C2 | VN | Data | RTV |
| Mission 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| Mission 2 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 1 |

The mission input will be a combination of deterministic and stochastic parameters. As an example, clouds can have static positions, pattern-defined mobility or random mobility. The communication events will also be distributed stochastically over time, and hence may differ from one simulation to the other, although the total communication load may be a predefined parameter. Interference from the environment may also be either defined deterministically or as a stochastic parameter. Propagation parameters may also be analysed probabilistically.

### 8.4.1 Definition of success

A mission trial (the execution of a mission with one set of mission parameters) is defined as successful when all the required services are successfully operated. A service is defined as successful when it fulfils the metrics' requirements attached to this service. The relation between metrics and services needs to be worked out in the future work.

In order to characterise mission success, when taking into account also the stochastic parameters of the missions, enough simulations per vignette are required such that the results will be statistically significant. For each run of the simulation model, the simulation results either meet the mission success criteria defined above (YES), or do not meet the success criteria (NO). The collection of runs gives an average percentage of mission success as a single-value output.

### 8.4.2 Services overview

The services that are relevant to operational missions are:

- **Push To Talk (PTT):** The basic half-duplex broadcast voice service used in tactical operations. It is often referred to as Combat Net Radio.
- **Blue Force Tracking (BFT):** Service providing a common view of the location of friendly forces in a region.
- **Command and Control (C2):** Messaging service providing a shared operational overview that assists in the planning and control of forces and operations.
- **Voice nets (VN):** One-to-one or one-to-many voice call service.
- **Data:** Packet data service providing access to a data network. Real-time requirements are less stringent than in voice communications.
- **Real-Time-Video (RTV):** Real-time video transfer e.g. from deployed sensors in the scenario.

## 8.5 SERVICES DESCRIPTION

Several services are supported in a cloud. In this section, we will list and describe the most relevant services.

### 8.5.1 Push-To-Talk (PTT)

It is understood that the voice service uses a vocoder, yielding a constant bit rate during the call. Amongst these vocoders, MELP (mixed excitation linear prediction) is a US Department of Defense speech-encoding standard that was invented in 1995 and then standardized in 1997 as MIL-STD-3005 for communicating at 2400 bit/s. A later version, MELPe (MELP enhanced), was adopted in 2002 as STANAG 4591 (NATO Standardization Agreement). The 2.4 kbps MELP standard is still intelligible with a bit error rate of 1%.

The traffic model for the voice calls uses two exponential distributions with mean service time $\lambda$ (duration of the call) and mean idle time $\mu$ (silence). This allows a simple modelling of the calls for non-continuous transmission services.

- Voice will have an exponential distribution of 10s mean service time and 50s mean idle time (giving in average 60 PTT-calls/hour).
- In the case of an attack of the convoy, voice will have exponential distribution of 10s mean service time and 10s mean idle time (giving in average 180 PTT-calls/hour).

#### 8.5.2 Blue Force Tracking (BFT)

Blue Force Tracking can be modelled as a deterministic packet-based service. The message size is 100 bytes of data that is coded and spread.

From the Enhanced Position Location Reporting System (EPLRS), there is one 2ms message every 60s. It operates in UHF band (420-450MHz) and is frequency hopped over eight 5 MHz channels at 512hops/s.

#### 8.5.3 Command and Control (C2)

The Command and Control data service can be modeled as a packet-based service with two exponential distributions with mean service time $\lambda$ (according to the size of the packet) and mean idle time $\mu$ (silence), 6 command and control data/hour. The message size is variable (2-3 kbytes for instance).

#### 8.5.4 Voice Networks (VN)

For voice networks the data rate is the same as for PTT, 2400 bits/s at an error rate of $10^{-2}$. The traffic model is the same as for PTT, with more frequent messages as the nodes also pass messages from other nodes. The packet modelling uses two exponential distributions with mean service time $\lambda$ and mean idle time $\mu$. This allows having a simple modelling of the packets for non-continuous transmission services. Voice will have exponential distribution of 10s mean service time and 10s mean idle time (giving in average 180 PTT-calls/hour).

#### 8.5.5 IP Data Applications

For intranet browsing it can be assumed that webpages can be either compressed or uncompressed, but they will not contain images. In an uncoded form they are fixed size of 20-100+kB, which will be 40-200+kB in coded form. We further can assume that the file stops transmitting when SNR falls below bottom level (i.e. there are no extraneous control packages). The file size includes ARQ retransmissions. The required BER is $10^{-2}$ on the coded file.

We need a traffic model with random interval between files and an exponential distribution with a mean of 100 ms, Files can take variable length of time depending on the achievable rates.

#### 8.5.6 Real Time Video (RTV)

For real time video streaming, Elbit Systems claims to provide the user with streaming video footage on the move at 115 kbps with 25 kHz VHF bandwidth. For low bandwidth RTV, which can be used for situational awareness, the following data rates are recommended in [1]:

- 384 - 768 kb/s: 352x288, 352x240 or 320x240 at 24-30 frames per second.
- 192 - 384 kb/s: 352x288, 352x240 or 320x240 at 12-15 frames per second.
- 56 - 192 kb/s: 352x288, 352x240 or 320x240 at 6-7 frames per second.
- < 56 kb/s: 176x144, 176x120 or 160x120 at 5-15 frames per second.

Bandwidth recommendations for higher resolutions and frame rates are also available in [1]:

- UHF: 300kb/s on 1MHz channel.
- VHF: 32kb/s on 25kHz channel.
- Required BER $10^{-3}$ (coded signal).

## 8.6 PERFORMANCE ASSESSMENT

There are four basic categories of metrics that can be measured:

- Terminal, metrics that can be measured at a single radio.
- Link, metrics that can be measured between two terminals.
- Network, metrics that can be measured at the network level.
- Cognitive, metrics that can be improved due to cognition.

In all areas there will be non-definable metrics that can only be looked at on a case-to-case basis. For example, complexity versus feasibility, any problem can be solved if there are enough resources put to it, considering enough time put on it. It would probably not be worth the cost of spending the total budget of a nation over the next thousand years on gaining 3 dB of improvement, but it could be done. As a system becomes more complex reliability could be affected and trade-offs have to be studied, but what is acceptable for one system development may not be acceptable for another.

### 8.6.1 Terminal

From the terminal point of view there are three main areas that need to be evaluated: 1) Bandwidth 2) Power and 3) Receiver sensitivity. Using bandwidth to help in another area is an acceptable trade-off, however, it is important to know the cost. By measuring bandwidth at the transmitter, you can obtain a baseline of what the communication system needs in order to function. Both output power and the power being drawn by the radio are very important. Output power determines the range of communications, the robustness in respect to jamming, and the system's interference to other systems. The power being used by the communication system will determine the battery life and the infrastructure necessary to handle the power. The sensitivity of the receiver needs to be measured, this will show the minimum energy that the receiver will recognize and accept as a signal that information can be gathered from. The basics of good RF design (clean output signal, good filtering, low spurious signal) will be shown through the power, bandwidth, and sensitivity measurements.

### 8.6.2 Link

When looking at the link metrics both receive and transmit measurements are factored in. The environment will have a major effect on the ability of the link to allow communication. Metrics for the evaluation of the link include: Signal to interference and noise ratio, link availability, link outage probability (usually calculated as a function of the Shannon capacity of the link which in turn becomes a function of the SINR for Gaussian channels specifically), probability of error, packet loss, robustness (how much power does a jammer need to disrupt the link), covertness (LPI vs. AJ, probability of detection, probability of false alarm), quality of service, data dependents (latency, error protection/error resistance, priority, data rate). In case of the link the over-the-air time is determined by the overhead associated with the type of data and the processing of the data. Over the air time will play a bigger role when other factors are added in.

*8.6.2.1 SINR computation*

To compute the SINR for the typical narrowband link in the cloud for each simulation realisation:

1) From the maximum transmit power, compute the maximum range based on the target SNR:

a) For LOS case, use exponential path loss model with exponent $\alpha = 2$.

b) For NLOS case, use exponential path loss model with exponent $\alpha = 3$.

2) Determine the distance between nodes on typical link:

a) Randomly draw from a uniform distribution, between epsilon and maximum range (epsilon is a minimum range that prevents the transmitter and receiver from being at the same point).

3) Compute path losses within the cloud, which are fixed for each simulation realisation:

a) For LOS case, use distance in exponential path loss model with exponent $\alpha = 3$.

b) For NLOS case, use distance in exponential path loss model with exponent $\alpha = 3.5$ to obtain mean path loss, multiply by random path loss drawn from Rayleigh distribution, derived from complex normal distribution with zero mean and unit variance.

These path loss values will be used to compute the actual received power and SINR in the implemented resource allocation algorithms.

For several frequency channels, this process is repeated. The parameters (distances & path loss exponents) remain the same. For the NLOS case, a different random Rayleigh path loss component is drawn for each channel. For UHF NLOS channels with frequency selective fading, the channel should be considered as multiple narrowband channels, each with independent Rayleigh fading following the same distribution described above for the narrowband NLOS case. For the wideband LOS case, the channel is assumed to be frequency flat.

SINR mapping uses the AWGN BER/PER curve for VHF channels and the wideband LOS case. For the wideband/UHF NLOS case, the Rayleigh fading BER/PER curve must be used. At each simulation time event, the SINR value at a given cloud is deduced from the interference coming from the other clouds, for each channel. From this SINR, we then compute the corresponding metrics' values according to a mapping table.

### 8.6.3 Network

When looking at the network metrics scalability is important. Usually a network is made up of more than two terminals which necessitates looking at:

- the capacity of the network (amount of data that can flow in the network).
- session outage probability.
- throughput (the amount of packet transmissions without rejections and with a finite delay).
- goodput (the amount of useful data that make it through the system).
- delay.
- the number of users.
- probability of error (introduced by multiple users).
- header vs. payload.

- network compatibility (interoperability, heterogeneous vs. homogeneous).
- number of nodes.
- speed of nodes.
- type of nodes.
- time to reach network stability, and time to reconfigure the network.

Over the air time is very important at the networking level, the longer a terminal is transmitting the less time is available for other users and the more bandwidth a terminal is using the less there is available for others. Over-the-air time is measured end-to-end (source-to-destination, including any return trips, control channels, hops, and re-transmits).

### 8.6.4 Cognition

When adding in cognition the network cannot be degraded and the cognition must solve an existing communication problem. Metrics to look at are: time to reach a solution set, additional processor power needed for cognitive functions, crosstalk/interference caused by cognition, mission effectiveness, cognitive overhead (what is gained vs. what is lost when using cognition).

## 8.7 OTHER ISSUES

At this preliminary stage of the simulation methodology, we cannot foresee all the issues that will be covered, and this section will be left open to address further issues. For instance, the cost of signaling will need to be evaluated. Indeed, the maintenance of the network (link layer and networking) is done through signaling that hampers the data throughput. The radio cognitive implementation needs also signaling to exchange decisions like frequency channel changes. This signaling needs to be taken into account as well as the period of time when the radio will not be transmitting while changing its frequency (if not seamless).

## 8.8 REFERENCES

[1] Motion Imagery Standards Profile 6.1, DoD/IC Motion Imagery Standards Board, Online: http://www.gwg.nga.mil/misb/docs/MISP61.pdf

# Chapter 9 – SCENARIOS AND VIGNETTES

## 9.1 INTRODUCTION TO THE VIGNETTE BASED MODELING

During the RTG's meeting in Florence in January 2010, Enrico Casini from DOP-CAT9 presented and offered to the group a set of (NATO Unclassified) scenarios and vignettes typical of coalition tactical operations. The presentation was based on an extract of the scenarios and architectures presented in the NATO report "Ad-Hoc Networking for NATO- Operational Benefits" [101]

The contribution offered three scenarios that can be considered typical wireless land tactical domain. These were derived considering the NATO Response Force (NRF) as major user because it embodies the changing nature of NATO and because its land component is provided by many nations.

Each scenario was described in terms of entities involved in the action, Information Exchange Requirements (IER), required services and associated Quality of Service (QoS), throughput, traffic load, and security. The presentation concluded with some questions about how cognitive radio could help enhancing the operation through radio reconfiguration and the security management aspects that go with it.

Based on the input provided by Enrico in this meeting, the group took the action to further elaborate the vignette "convoy protection" derived from the scenarios, and add more specific details such that it could form a basis for simulation of various cognitive radio behavior principles.

## 9.2 RTG035 VIGNETTE DERIVATION: PREVENTING THE HIJACKING OF AN AID CONVOY VIGNETTE

### 9.2.1 Vignette description

#### *9.2.1.1 General scenario*

NATO coalition troops are involved in a Peacekeeping Operation. A peacekeeping operation is defined as "a Peace Support Operation (PSO) following an agreement or ceasefire that has established a permissive environment in which the level of consent and compliance is high, and the threat of disruption is low. The use of force by peacekeepers is normally limited to self-defence."

The area in which the troops are operating is quite stable. NGOs are supplying the local people with food and medical equipment. In the last few weeks, however, several aid-convoys have been subject to attacks by rebels situated in and near the area of Spa.

The objective in this tactical vignette is to prevent the hijacking of such a humanitarian convoy. While doing this, the NATO coalition should avoid collateral damage and non-combatant casualties. The NGOs wishes no direct protection for this convoy. However, NATO forces in the area have been informed of the convoy's route and intended timings of a possible attack and have decided to supervise the route from a distance.

#### *9.2.1.2 Description of the vignette*

The convoy is composed of 4 trucks, transporting food and medical supplies. The trucks are progressing with a speed of 50 km/hr on the N629 west between the villages Tiege and Spa (see Figure 9-1: Preventing the Hijacking of an Aid Convoy). The inter distance between the trucks about 100 m. In Spa, they will take the N62 direction west. In the past few weeks, rebel activity has been reported in the area of Spa. The NATO coalition troops have been informed of a possible attack just outside of Spa on the N62.

To protect the convoy, the NATO PSO force decided to send a BEL company (Co. A of the 2nd mechanised infantry battalion) to the area of Spa. Mechanised infantry is infantry equipped with armoured infantry vehicles (AIV), 1 AIV per section, 4 per platoon. The BEL Co. has in support of the operation two helicopters from a FRA HELI Squadron. The first flight of the FRA Squadron is stationed on an airport in the neighbourhood and protected by a GE light infantry platoon.

The position of all units with their coordinates are given in Figure 9-1, Table 9-1 and Table 9-2.

*9.2.1.3 Pictorial view of the vignette*

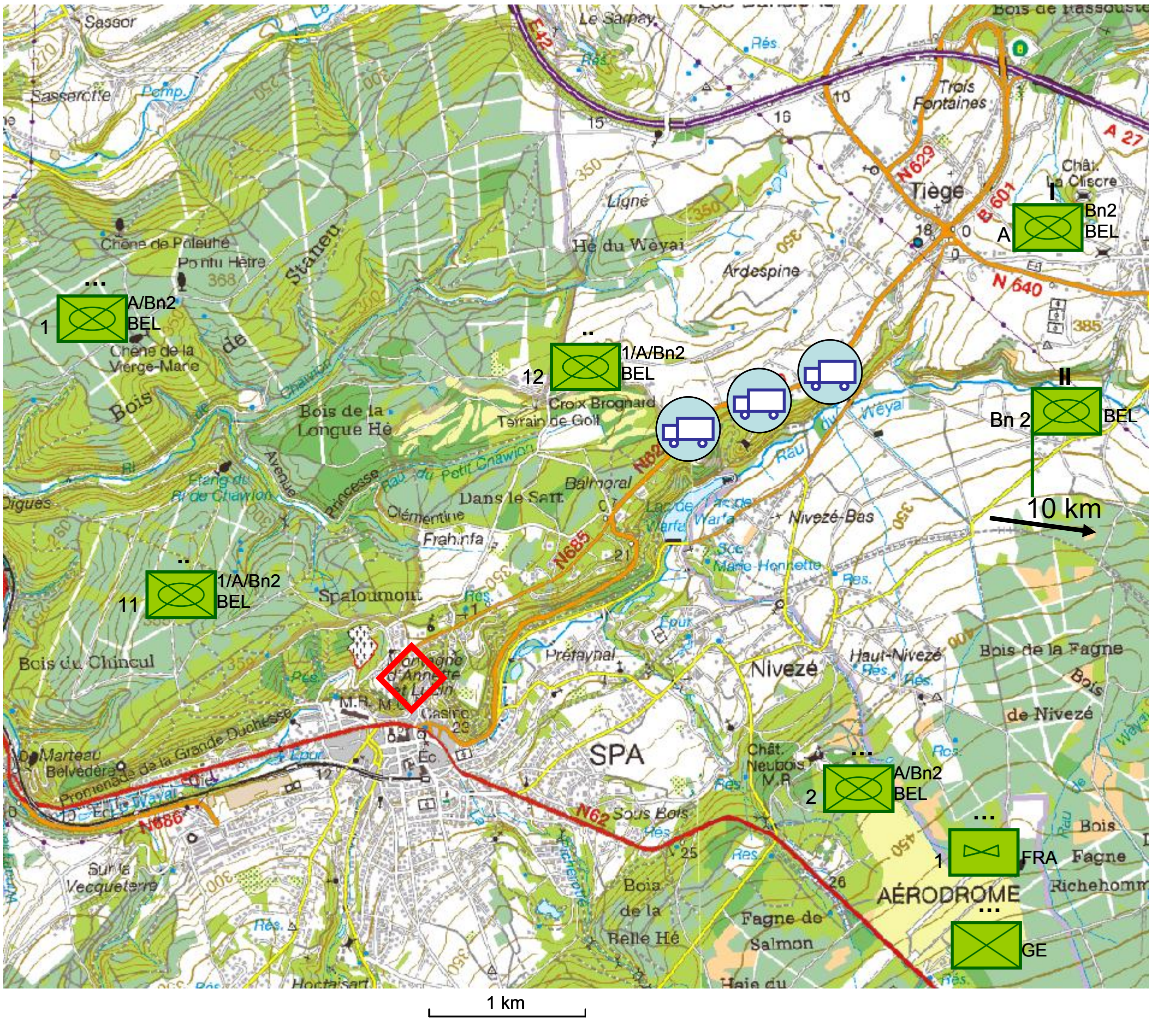



**Figure 9-1: Preventing the Hijacking of an Aid Convoy.**

The represented area of operation is about 7*7 km around the region of Spa. The coordinates of some characteristic points and of the troops are presented in Table 9-1 and Table 9-2. All coordinates are in UTM format (with a resolution of 10 m).

**Table 9-1: Coordinates of Characteristic Points.**

| Site | Coordinates |
|---|---|
| Tiège | 31U GS 0650 0045 |
| Spa | 31U GR 0395 9686 |
| Airport | 31U GR 0652 9616 |

**Table 9-2: Coordinates of Headquarters and Troops.**

| Unit | Description | coordinates |
|---|---|---|
| HQ Bn 2 (BEL) | | |
| Co. A of Bn2 (BEL) | Tiège Château La Clisore | 31U GS 0740 0054 |
| Pl 1 of Co. A (BEL) | Chêne de la Vierge-Marie | 31U GR 0135 9963 |
| Sec 1 of Pl 1 (BEL) | Bois du Chincul | 31U GR 0145 9973 |
| Sec 2 of Pl 1 (BEL) | Crois Brognard | 31U GR 0402 9922 |
| Pl 2 of Co. A (BEL) | Château Neubois | 31U GR 0565 9703 |
| 1 Flight Lt Avi (FRA) | Aérodrome | 31U GR 0652 9616 |
| Pl Lt INF (GE) | Aérodrome | 31U GR 0652 9616 |
| Rebels | Spa Montagne d'Annette | 31U GR 0328 9761 |

### 9.2.2 Radio communication architecture

#### *9.2.2.1 Organisation of a mechanised or light infantry battalion*

A typical organisation of a mechanised or light infantry battalion (Bn) is presented in Figure 9-2. A Battalion (Bn) is composed of 4 companies. Each company has 3 platoons. There are 3 sections per platoon. In total, one platoon has 4 AIVs (1 per section and one for the platoon leader) and a jeep. Every vehicle is equipped with a radio.

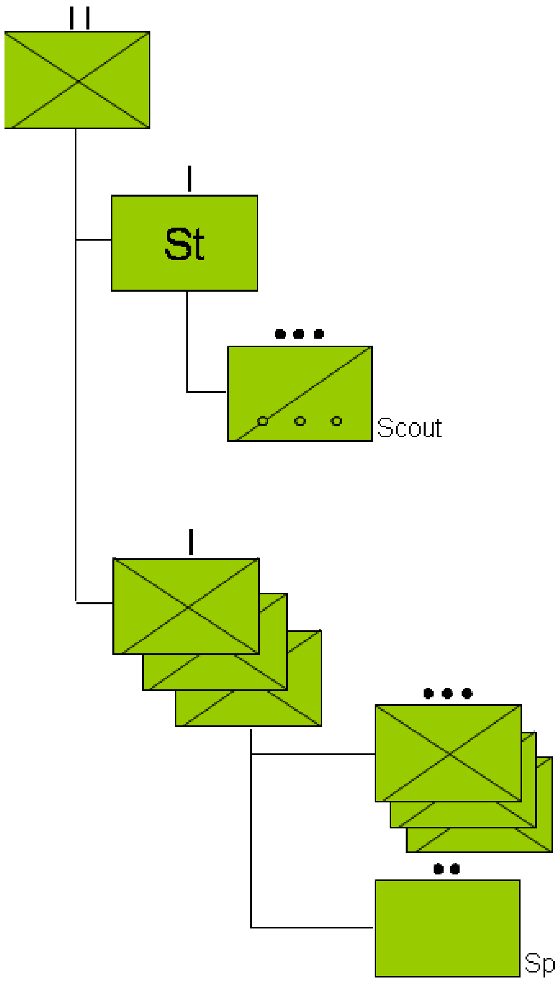



**Figure 9-2: Organisation of a Mechanised Infantry Battalion.**

*9.2.2.2 The radio communication architecture*

In this section, a typical radio communication architecture will be described. Please note that this architecture is just an indication that can be used as a realistic starting point for the simulations. It is based on a present or near future situation and will probably change with time and available technology.

The radio networks can be subdivided by their C2 level and their application. Under the level of a company, one can distinguish 2 or 3 radio networks: A company network for voice and data communications between the company commander and the platoons, a platoon network for voice and data and a section network. The data network in a platoon can be a flat network. If every soldier has a personal radio, this can lead to a network with up to 40 nodes. Table 9-3 summarises the different radio networks. For example, a platoon voice network is between the platoon and the 3 sections. Normally every vehicle is equipped with a radio (5 in total). In a dismounted scenario, the platoon commander and section commanders will in addition use their manpack radio, leading to 10 nodes in total. Note that the radio equipment used for the voice and data applications can be the same.

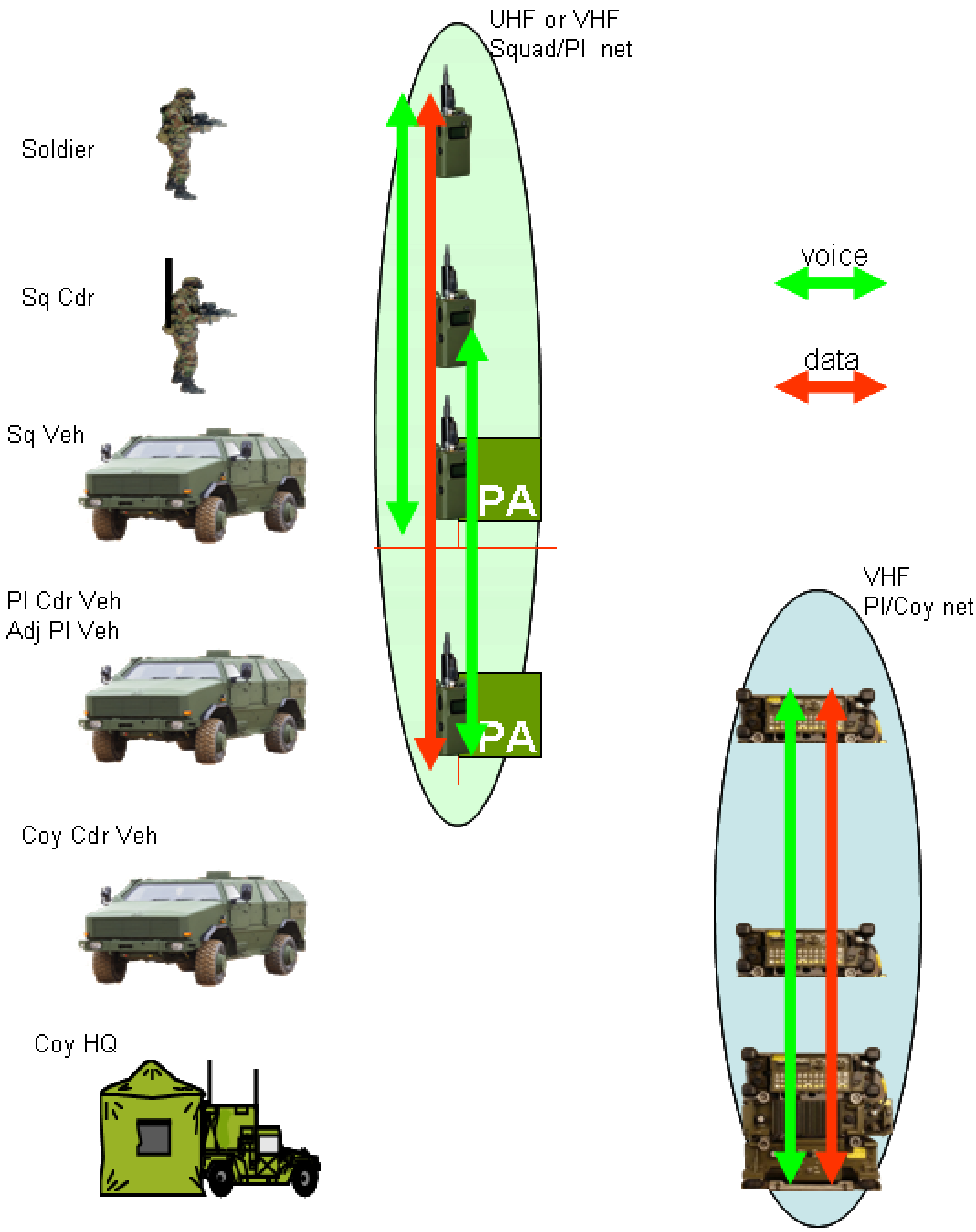



**Figure 9-3: Radio Architecture.**

**Table 9-3: The Radio Communication Architecture.**

| Radionet level | Application | Number of nodes | Band |
|---|---|---|---|
| Battalion net | Voice & data (C2) | 7 to 10 | VHF + HF ( + satcom) |
| Company net | Voice & data (C2) | 5 to 10 | VHF |
| Platoon voice net | voice | 5 to 10 | VHF (or UHF) |
| Platoon data net | Data (C2) | 5 to 10 (5 to 40) | VHF (or UHF) |
| Squad voice net | Voice | 0 up to 11 | UHF |

The values in Table 9-4 can be used to characterise the radio equipment for the simulations.

**Table 9-4: Radio Equipment Characteristics.**

| Radio | Tx Power [W] | Distance [Km] | Service |
|---|---|---|---|
| HF | 100 | Long distance | Voice, (data) |
| VHF manpack | 0.5-5 | 3-8 | Voice, data (C2, SA,..) |
| VHF vehicle | 5-10 | 15-20 | Voice, data (C2, SA,..) |
| VHF vehicle +ampl | 50 | 25 | Voice, data (C2, SA,..) |
| UHF PRR | | 1 | Voice, data (C2, SA,..), ad hoc |
| UHF vehicle | | 10 | Voice, data (C2, SA,..), ad hoc |

### 9.2.3 Simulation settings and parameters

In this section, some simulation parameters are presented. Again, these parameters are just an indication that can be used as a starting point, but can be modified for the simulations.

**Table 9-5: Simulation Parameters.**

| Parameter | Value |
|---|---|
| Mobility model for the units | Stationary |
| Mobility model for the convoy | Constant speed, 50 Km/Hr |
| Frequency band VHF | 30-88 MHz, |
| Frequency band UHF | 225-400 MHz |
| Channel bandwidth VHF | 25 KHz |
| channel bandwidth UHF | Up to 5 MHz |
| Number of nodes | See Table 9-3 |
| Frequency hopping | Possible |
| Path Loss Model | Rural, Path Loss Exponent = 3.5 |
| Voice Traffic intra platoon | Mode: PTT<br>Codec: MELP, 2400 bit/s<br>Connection rate: 50 PTT calls per Hr,<br>Call duration: 2-10 s per call |
| Data Traffic intra platoon | BFT: 1 per minute per radio, 10 bytes/Msg<br>C2 data: 1 every 10 min, 200 bytes/Msg |

The most important sources of data traffic are:

- Situational Awareness (SA): Blue and Red force location, status and intent information like BFSA, RBCI and Target Identification.
- Command and Control (C2): planning, orders, overlays, messages and BFT (concatenated position updates from all friendly forces).
- BFT is the ability that provides commanders with near real-time location information of their own forces throughout the chain of command.
- Functional services (FS): for Combat Support (CS) and Combat Service Support (CSS). This includes information specific to certain types of units or commanding levels, e.g. Fire Support (Artillery and Close-Air-Support), MedEvac, Logistics and Supply Chain support.

Figure 9-4 gives an indication of the relative amount of data per source on the different battalion levels.

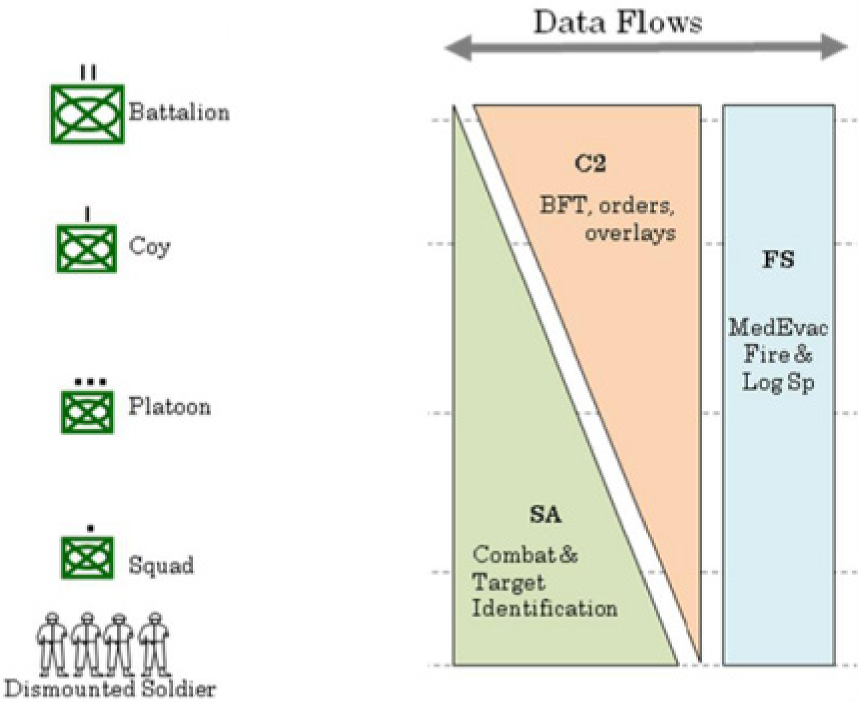



**Figure 9-4: Data Flows in a Battalion.**

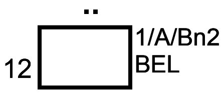
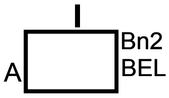
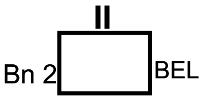
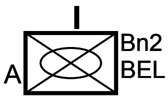
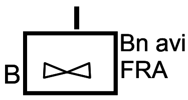
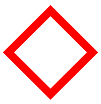
### 9.2.4 Possible conflicts

A list of some trivial potential problems, that could serve as a start for the simulations, is presented here. Note that this list is not exclusive:

1) The aid-convoy is on the same frequency as the data network of the platoons.
2) The rebels have a jammer and start jamming the platoon frequencies just before the attack.
3) The frequency used by the first Flight of the FRA Heli Squadron is the same as the frequency used by one of the platoons.
4) The aid-convoy has a wideband jammer against 'Radio Controlled- Improvised Explosive Device' (RCIED) threats, that may also affect the platoon frequencies/communication along the route.
5) Uncoordinated use of frequencies between GE light infantry Pl and BEL mechanised infantry Bn.

### 9.2.5 Legend

**Table 9-6: Legend for the Vignette.**

| | |
|---|---|
|   | A section: up to 10 soldiers. |
|   | Platoon (Pl): 3 sections<br><br>(Pl 1 of Co. A of a BEL Bn 2) |
|   | Company (Co.) / battery/squadron |
|   | Battalion (Bn) / battlegroup (BG) |
|   | mechanised infantry Co.<br><br>(Co. A of the BEL second mechanised infantry Bn) |
|   | Light aviation (Rotary wing aircraft) squadron |
|  | Rebels |

## 9.3 VIGNETTE MAPPING ACCORDING TO SIMULATION METHODOLOGY

In this paragraph we describe how a vignette can be mapped into clouds according to the simulation methodology. Typical battalions are hierarchically subdivided into companies and platoons. These hierarchically organized units schematically evolve in concentric areas of higher ranges for battalions than for companies and platoons. Non-governmental organisations (convoy) and the enemy have also their own communication infrastructure which can be mapped in terms of clouds. We worked on the previous vignette and came up with the following proposal with their characteristics:

- Cloud #1: BE Company
  - Voice: VHF
  - Data: VHF
  - Platoon #1 - BE
  - Platoon #2 – BE
- Cloud #2: BEL platoon #1
  - Voice: VHF
  - Data: VHF
- Cloud #3: BEL platoon #2
  - Voice: VHF
  - Data: VHF
- Cloud #4: FR Company
  - Voice: VHF
  - Data: VHF
  - Platoon – FR (Voice, Data: VHF)
- Cloud #5: GE Company
  - Voice: VHF
  - Data: VHF
  - Platoon – GE (Voice, Data: VHF)
- Cloud #6: Convoy
- Cloud #7: Enemy

These clouds are represented in Figure 9-5.

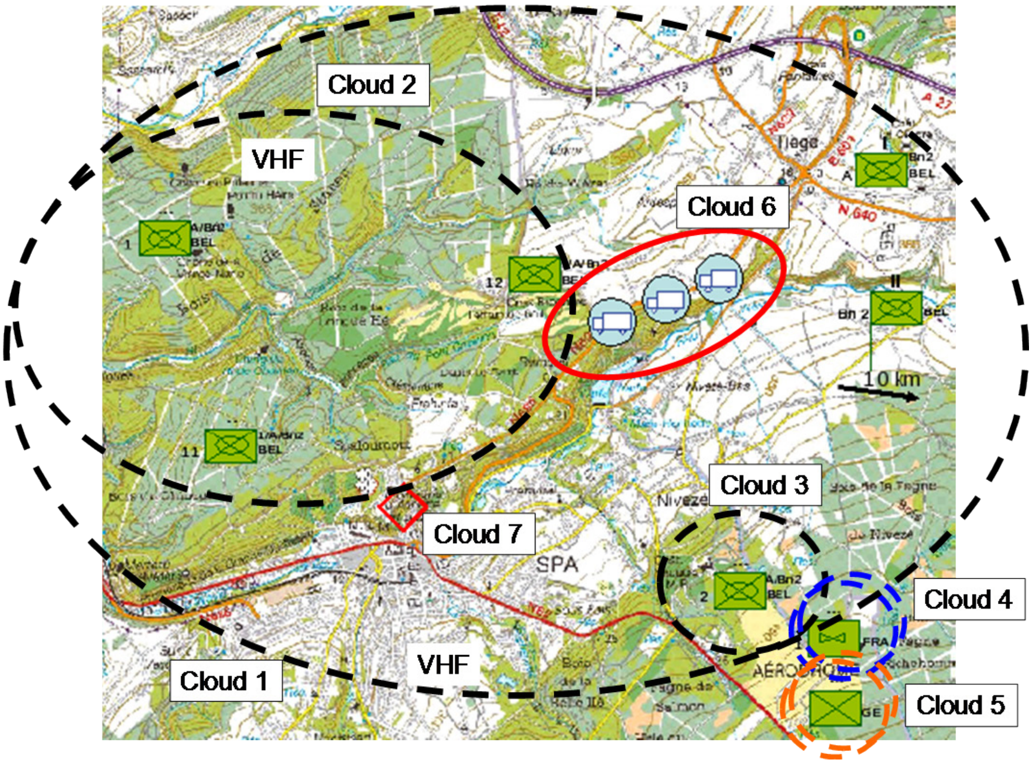



**Figure 9-5: Mapping of the "Preventing the Hijacking of Aid Convoy" Vignette into Clouds.**

The cloud approach is well suited to legacy tactical radios which have the ability to control output power manually. The radios can vary transmission range from approximately several hundred meters to several kilometers. Adding a power amplifier increases the Line of Sight (LOS) range to approximately several tens of kilometers. These ranges are for planning purposes only since terrain, weather, and antenna height have an effect on transmission range. The variable output power level allows users to operate on the minimum power necessary to maintain reliable communications, thus lessening the electromagnetic signature of their radio sets. This ability is of particular importance at major command posts, which operate in multiple networks. The cloud approach is also well suited to future cognitive tactical radios in which the transmit power control can be set up automatically by sensing the electromagnetic environment and can use dynamic spectrum management to improve the coexistence of multiple networks. Therefore, the simulation methodology will be able to make a comparison between legacy tactical radios and cognitive tactical radios and also between different cognitive radio approaches.

## 9.4 REFERENCES

[1] NATO Consultation, Command and Control Agency Technical Note 1331 “Ad-Hoc Networking for NATO –Operational Benefits” (title NATO Unclassified), The Hague, The Netherland, December 2007 (NATO Unclassified).

# Chapter 10 – CONCLUSIONS AND RECOMMENDATIONS

This Research Technology Group (RTG) has collected research contributions, discussed and distributed ideas on CR and merged these into this report. It has been clear for the members of this group, that CR is needed and useful for military users. However, more work is needed and CR systems are far from mature. Based upon their work, the group has come up with the following recommendations:

1) This RTG has been working on the development of a simulation methodology to investigate the effectiveness of CR strategies in dynamic conditions. Ongoing work is needed to continue this effort and to determine which strategies are most effective. Therefore it is recommended that: the subsequent RTG continues to develop the methodology for evaluating the dynamic coordination of coalition networks.

2) Scenarios or vignettes should be developed and simulated that establish whether cognitive radio techniques do outperform legacy systems and offer new solutions to existing communication problems. Therefore it is recommended that: the baseline for using legacy systems is established for vignettes to compare against a cognitive radio system for those same vignettes. This will show some of the benefits of cognitive radio and lays the foundation for collaborative research to be conducted in the future to benefit all of NATO.

3) The behavior of systems that are highly adaptive will have to be constrained by policies. Appropriate policies need to be developed and tested, in preparation for the introduction of CR technologies into the marketplace by industry. Therefore it is recommended that: NATO (spectrum managers and the subsequent RTG) consider appropriate coalition policies for dynamic spectrum access.

4) For cognitive radio systems introduced in the military domain there is a need to be aware of any additional vulnerability issues that are opened up. It is recommended that these vulnerabilities are taken into account by system designers.

5) One of the main challenges for military cognitive radio systems is how to introduce these systems in the military. For this, it is recommended that: NATO develops of a realistic roadmap, keeping in mind that there will always be a transition period in which legacy systems have to coexist with cognitive systems.

6) In our opinion, a realistic first step in this roadmap would be the creation of dedicated Military Open Spectrum band (MOS-band), comparable with the civil ISM band, exclusively for cognitive radio systems. This MOS-band will guarantee that there will be no interference with legacy systems. Moreover, by introducing this MOS-band the system requirements of the cognitive radio systems can be relaxed. It is recommended that the NATO C3 Board starts the necessary procedure to define such a band within the NATO harmonized frequency bands.

7) Once CR policies have been developed, systems (radio and other spectrum users) must be evaluated to ensure their compliance and monitored when in use. Therefore it is recommended that: NATO develops testing and evaluation protocols to evaluate and monitor dynamic spectrum users.

8) Simulations will be useful to identify promising strategies for more effective spectrum access, but they will not be adequate to fully understand the capabilities and challenges introduced by the complex behaviour of this technology. For the moment the gap between theoretical concepts and real implementations is still too big. This again stresses the importance of creating a "Military open spectrum" band within the NATO harmonized frequency bands to encourage the development of future technologies and to test their performance under real conditions.

9) The importance of the spectrum domain to successful operations cannot be underestimated. Spectrum is increasingly becoming a battlespace, and lack of connectivity can result from malicious attack or from congestion due to high demand. Modern operations rely more and more on the timely exchange of information, and loss of connectivity can have significant consequences. While the technology is being developed to improve the robustness of radio systems to these conditions, it is essential that training exercises reproduce these spectrum access conditions to prepare forces effectively and to ensure radio systems are able to operate as required.

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**14. Abstract**

In NATO, frequency management is based on a static allocation of spectrum bands and frequencies. While this is effective for interference avoidance, and is necessary for some spectrum users including many legacy systems, it prevents dynamic reuse of allocated bands that are not in use. For modern radio systems that are more tolerant of interference, a more effective spectrum access strategy would allow radios to adapt their operating frequencies in response to the changing propagation and interference environment. This strategy is the basis of the cognitive radio (CR) technology concept.

A more dynamic approach to spectrum access, as provided by CR technology, is expected to bring a number of benefits, in particular, more effective use of spectrum to increase usable bandwidth in congested theatre of operations. This should provide increased robustness to dynamic conditions, but does not mitigate the need to increase the spectrum efficiency of future systems.

The objectives of this NATO RTG were to review and synthesize the R&D in CR technologies for military applications and to investigate the technology and its implications for future NATO operations.

This NATO RTG has focused on the coexistence of coalition tactical networks operating in the same theatre of operations, i.e. cognitive radio networks that are not centrally coordinated – this is considered to be an important factor in the successful introduction of this technology into the coalition theatre that is not being considered elsewhere.

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