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Cognitive Radio Techniques For Assured Communications

Final report

T.J. Willink

Defence R&D Canada – Ottawa

Technical Report
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Abstract

The objective of the Technology Investment Fund project “Cognitive radio techniques for assured communications” was to investigate the potential of advanced radio devices to provide robust and reliable communications in highly congested spectral conditions. Cognitive radio is commonly associated with accessing spectrum that is allocated but currently unused, i.e., dynamic spectrum access. Commercial and academic interest has focussed on homogeneous spectrum reuse, mainly with static primary and secondary users. For defence applications, the environment is expected to be dynamic and heterogeneous, hence it is more appropriate to apply ‘cognition’ to respond to changes in its operating environment by appropriate adjustments of the radio and network parameters, not limited to operating frequency.

Résumé

Le projet sur les techniques de la radio cognitive pour des communications assurées du fonds d’investissement technologique avait pour but de déterminer si des appareils radio de pointe pouvaient offrir des communications robustes et fiables malgré un spectre très encombré. On associe généralement la radio cognitive à l’accès à une partie attribuée mais inutilisée du spectre, c’est-à-dire à l’accès dynamique au spectre. Le milieu universitaire et les entreprises ont concentré leur intérêt sur la réutilisation homogène du spectre, surtout avec les utilisateurs statiques primaires et secondaires. En ce qui concerne les applications pour la défense, on s’attend à ce que l’environnement soit dynamique et hétérogène ; il est donc plus pertinent de recourir à la « cognition » pour réagir aux changements de l’environnement opérationnel en ajustant adéquatement les paramètres des radios et des réseaux et en ne se limitant pas à la fréquence de fonctionnement.

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Executive summary

Cognitive Radio Techniques For Assured Communications

T.J. Willink; Defence R&D Canada – Ottawa;
DRDC Ottawa TR 2010-004; January 2010.

The concept of cognitive radio was introduced in the late 1990s as a device with self-awareness and the ability to make autonomous decisions. The involvement of the US FCC and the IEEE Standards Committee has focussed attention on dynamic spectrum access, in which the radio senses its RF environment and selects a portion of unused spectrum for its own use. This aspect has attracted considerable interest because the spectrum is fully allocated over the regions of commercial interest for wireless communications.

The dominating academic and commercial vision of cognitive radio currently is homogeneous and static – the IEEE wireless regional area network proposes exacting specifications for fixed-location secondary radios operating in a region of spectrum where the fixed primary users have well-defined characteristics. R&D in this area has demonstrated the extreme challenges in achieving an adequate level of self-awareness, in particular, of RF occupancy to satisfy regulatory bodies.

The defence application for advanced radios is heterogeneous and dynamic. Legacy radio equipment and other spectrum-occupying devices have a wide range of on-air characteristics, and new radios that would be introduced would be similarly diverse. At the same time, the interference-avoidance requirements may be less stringent due to the lack of commercial influence, making spectrum reuse more feasible. The trend to network-enabled capabilities and the essential mobility of tactical environments means the focus of defence R&D in this area is on mobile radio networks. The introduction of ‘cognition’, or more accurately ‘context-awareness’, in this case should include more than dynamic spectrum access. The radio network should respond to changes in its operating environment, including RF interference and propagation, user demands and topology, by appropriate navigation of a multi-dimensional tradespace, which may include spectrum access but is not limited to it.

The objective of the Technology Investment Fund project “Cognitive radio techniques for assured communications” was to explore the potential of this new technology for defence applications, in particular to achieve robust and reliable communications in congested spectrum. Some aspects of the work built on previous expertise while others reflect the development of new expertise. Numerous insights were gained, which have led to new R&D directions, and technical contributions were achieved in a range of areas. The project outputs have been included in international journals and conference proceedings, and have also influenced the defence R&D community through presentation in NATO and TTCP fora.

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Cognitive Radio Techniques For Assured Communications

T.J. Willink ; R & D pour la défense Canada – Ottawa ;
DRDC Ottawa TR 2010-004 ; janvier 2010.

Le concept de la radio cognitive a été introduit vers la fin des années 1990 ; on l'a alors présenté comme un dispositif conscient de son environnement et capable de prendre des décisions autonomes. La participation du Standards Committee de l'Institute of Electrical and Electronics Engineers (IEEE) et de la Federal Communications Commission (FCC) des États-Unis a concentré l'attention sur l'accès dynamique au spectre, selon lequel la radio détecte les radiofréquences environnantes et choisit une portion inutilisée du spectre à exploiter. Cet aspect a suscité un intérêt considérable puisque les portions du spectre ayant un intérêt commercial pour les communications sans fil sont déjà entièrement attribuées.

Actuellement, la vision commerciale et universitaire dominante de la radio cognitive est homogène et statique ; le réseau régional sans fil de l'IEEE propose d'exiger des spécifications pour les radios secondaires fixes qui sont exploitées dans une portion du spectre où les utilisateurs primaires fixes possèdent des caractéristiques bien définies. La recherche et développement (R-D) dans ce domaine a démontré les défis exceptionnels relatifs à l'atteinte d'un niveau adéquat de connaissance, et particulièrement d'utilisation des radiofréquences, pour satisfaire les organismes de réglementation.

L'application des radios de pointe pour la défense est hétérogène et dynamique. Le matériel radio traditionnel et autres appareils d'occupation du spectre possèdent une vaste gamme de caractéristiques de radiodiffusion, et les nouveaux appareils qui apparaîtront seront tout aussi variés. Parallèlement, les exigences visant à éviter tout brouillage pourraient s'avérer moins strictes en raison de l'absence d'influence commerciale, ce qui pourrait rendre plus praticable la réutilisation du spectre. La tendance relative aux opérations réseaucentriques et la mobilité essentielle des environnements tactiques signifient que la R-D pour la défense dans ce domaine se concentre sur les réseaux radio mobiles. Dans le cas présent, l'introduction de la « cognition » ou, plus précisément, de la « connaissance du contexte » ne devrait pas se limiter à l'accès dynamique au spectre. Le réseau radio devrait réagir aux changements de son environnement opérationnel, ce qui comprend la propagation et le brouillage des radiofréquences, les demandes des utilisateurs et la topologie, grâce à une navigation adéquate dans un espace d'échange multidimensionnel qui peut comprendre, entre autres, un accès au spectre.

Le projet sur les techniques de la radio cognitive pour des communications assurées du fonds d'investissement technologique avait pour but d'étudier les éventuelles applications de cette nouvelle technologie à la défense, et plus particulièrement d'offrir des communications robustes et fiables malgré un spectre très encombré. Certains aspects des travaux

ont tiré avantage de connaissances antérieures, alors que d'autres ont montré le développement de la nouvelle expertise. Le projet a donné naissance à de nombreuses idées et inspiré de nouveaux sujets de R-D. Des contributions techniques ont été offertes dans un grand nombre de domaines. Les résultats du projet ont été intégrés dans des revues internationales et les actes de congrès et ils ont influé sur le milieu de la R-D pour la défense lors de présentations à des activités de l'Organisation du Traité de l'Atlantique Nord (OTAN) et du Technical Cooperation Program (TTCP).

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1 Introduction

This is the final report for the Technology Investment Funding (TIF) project “Cognitive radio techniques for assured communications”, April 2006 – March 2009. The project was undertaken at the Communications Research Centre Canada.

This report describes the project objectives and rationale, and provides the context for the research and development that was initiated in this project. An overview of the technical contributions achieved by the project team is presented and an extensive list of project outputs, in the form of journal and conference papers as well as technical reports, is provided as the source of more detailed information.

1.1 Motivation

Many of the new technologies that will be introduced into the operational theatre in the next decade and forward will be dependent on access to the electromagnetic (EM) spectrum, not just in the conventional domains of sensors, electronic surveillance and C4ISR, but also for advanced capabilities such as remote command and control of weapons and counter-IED. The expansion of communications to provide wireless links through all the echelons, the networked nature of these new communications devices and the mobility of the users, all place increased demands on the available spectrum.

At the same time as the defence demand for spectrum is anticipated to increase, there is a surging demand in the commercial sector, as consumers are presented with a plethora of devices that enable real-time, high-bandwidth applications such as video and file downloads. These demands increase the monetary value of the spectral resource, as evidenced by the auction for cellphone frequencies in mid-2008, which yielded over $4b for 10-year leases covering 105 MHz bandwidth. The commercial demand and the potential for high revenues for the government put pressure on the defence spectrum allocations.

New concepts in spectrum management are being considered in both the commercial and defence arenas. In particular, dynamic spectrum access (DSA) is an alternative to the conventional fixed allocation approach. In DSA, users may sense and search for unused spectrum or may negotiate with a centralised spectrum management facility for short-term leases. While these approaches may open up access to new spectral bands, advanced spectrum management tools also occupy spectrum for information exchange, hence it is necessary to evaluate whether these tools provide a net benefit in a highly dynamic environment.

Another important feature in advanced communications technologies is improved spectral efficiency, whereby users and networks fine-tune their operating parameters to take maximal advantage of their operational requirements and environments. Again, there is a need to evaluate the costs vs. benefits as adaptivity has conventionally been focussed on point-to-point rather than networked communications. Based on previous R&D, it is considered that advanced, context-aware radio and network adaptivity has a high potential for increasing the spectral efficiency of communications systems.

1.2 Objectives

The primary objective of this work was to gain the necessary insight into the environment in which the cognitive radio is required to operate, and to explore some of the key aspects of applying this knowledge to tactical link and network communications.

Three specific areas were initially identified for investigation: interference control, the use of geographic awareness to adapt radio parameters, and the use of cooperative networks.

The focus of the actual research tasks changed somewhat between the proposal submission in June 2005 and the project's completion in March 2009, in response to research findings as well as the progress made in related areas in the academic and commercial arenas. However, the primary objective remained the focus throughout.

2 Context

Since the term ‘cognitive radio’ was introduced in the late 1990s, it has been been adopted to apply to many different systems, including software-defined radio implementations and radios with the capability to adapt various parameters such as waveforms or frequency. The “cognitive” label has also been applied in other technologies, e.g., cognitive radar [G37], which have similar ranges of interpretation. A summary of the changing context of cognitive radio is given here.

2.1 Original vision of CR

The original vision of cognitive radio (CR), put forward by Mitola [G38], was of a device with self-awareness and the ability to make autonomous decisions, i.e., “cognition”. This device would be able to sense its location and EM environment, and select an appropriate provider, e.g., cellular telephone service, that would support the desired use at the required quality of service and the lowest cost. The vision included a degree of user awareness, integrating data from different sources, such as daily calendars, to make autonomous decisions about collecting information, e.g., weather maps or bus schedules, that might be required by the user.

As part of Mitola’s concept of cognitive radios, a “rent-a-channel” protocol was proposed, whereby the device might negotiate with spectrum licence holders for short-term leases of their spectral allocations.

This view of CR requires a highly capable cognitive engine, operating on a software-defined radio (SDR) platform that would provide flexible operating modes, in particular multiple wireless communications standards for indoor and cellular use. This platform would need to provide adaptable carrier frequency capabilities, requiring complex RF capabilities such as adaptive filters and antennas.

While much of Mitola’s original work focussed on the idea of ‘cognition’ and ‘sense of self’ within the radio device, the aspect that attracted the most attention was the concept of dynamic spectrum access. Spectrum occupancy measurement results have shown that as much as 80-90% of the allocated bands in the 300 MHz-3 GHz range are unused [G39]. Similar observations have been made at CRC for the 300-1200 MHz range, see Figure 1. There has been considerable interest in enabling these unused bands to be accessed by ‘secondary’ users either when the ‘primary’, or authorised, users are not using them, or in a manner which will not cause interference to the receivers of the primary signal.

The US Federal Communications Commission (FCC) Spectrum Efficiency Task Force undertook a study of methods to reuse spectrum [G40], and recommended licence modifications to enable spectrum reuse either in time (when the primary user is not making use of the resource) or in space (beyond the reach of the primary user's service provision). They also recommended expanded access to licensed secondary users as well as unlicensed users, and to allow subleasing of spectrum by primary users with low occupancy requirements. However, preliminary efforts to allow secondary access to spectrum allocated to a primary user on a limited-interference basis were turned down by the FCC in 2007.

It should be noted that the concept of open access spectrum is not really new: there are currently ISM (industrial, scientific and medical) bands centred at 915 MHz, 2.45 GHz and 5.8 GHz, as well as several others both in the HF and SHF bands. These bands are generally given to unlicensed users, with no interference guarantees, such as Bluetooth, IEEE 802.11 wireless LANs, and remote-controlled toys. Several commercial devices operating in these bands have a channel-selection feature that adapts the operating frequency to avoid interference.

2.2 Current academic/commercial vision

The focus of most academic and commercial work in cognitive radio is in dynamic spectrum access. This has been spurred by statistics collected as part of the DARPA XG program that indicate that between 7% and 18% of the allocated spectrum between 30 MHz and 3 GHz is actually occupied [G39]. There has been an explosion in publications proposing methods for sensing and exploiting these spectral opportunities.

A particular focus for both academia and industry is the IEEE 802.22 standard that is in development (see Sec. 2.2.1, below), but there are other pockets of effort addressing niche applications such as Microsoft's 'KNOWS' for Wi-Fi-like systems with dynamic spectrum access [G41].

2.2.1 IEEE 802.22 WRAN

The IEEE 802.22 standard is under development for the reuse of the TV bands in the US for secondary users. There are no apparent plans, yet, to extend this spectrum reuse approach outside the US. Industry Canada has issued a Radio Policy [G42] that "licence applications will be considered, on a case-by-case basis, for advanced communications in remote rural communities". However, there is no indication that these communications systems would incorporate dynamic spectrum access, rather, they would be licensed for unused TV channels.

The recent change to digital transmission has reduced the spectrum occupancy of television signals. The degree of reduction depends on the format of the digital signal, hence there is a non-uniform mapping of the old analog bands to the new digital ones. As the analog signals are turned off, portions of the TV band (54–806 MHz, not continuous) are left unused in some locations. The IEEE 802.22 standard allows secondary devices, primarily fixed wireless regional area networks (WRANs, fixed point-to-multipoint networks with a radius of up to 30 km), to access these unused frequencies, on the condition that they do not cause interference to TV receivers within the reception range of the remaining TV transmitters, low power wireless microphones that also occupy these bands, or any other licensed user.

In determining the occupancy of the channel, it is expected that the WRAN systems will be assisted by geolocation information, as well as access to databases specifying the location and operation of known TV transmitters.

2.2.2 Other international activities

The IEEE P1900 Standards Committee has reformulated itself as the IEEE Standards Coordinating Committee on Dynamic Spectrum Access Networks, and has a call for proposals for standards projects in areas related to cognitive radio, such as DSA, wireless system coordination, etc. The aim is to focus on areas that might be incorporated into commercial products in the near to medium term [G43].

The Wireless Innovation Forum (formerly the SDR Forum) [G44] has established a Cognitive Radio Working Group (CRWG), which is currently working on a report, “Quantifying the Benefits of Cognitive Radio”. The CRWG is also attempting to write a specification for future spectrum databases and information exchange.

The Cognitive Communications Consortium (CogCom) is a new organisation comprised of about 30 universities and commercial research labs from around the world. The aim of CogCom is to further research in the areas that enable the application of cognitive principles to communications [G45]. CRC has been invited to join CogCom as the first Canadian, and first government research laboratory, member.

2.3 Defence vision

While the commercial and academic vision of CR remains focussed on standardised systems, resulting in a homogenous environment of secondary users operating in the spectrum allocated to primary users with well-defined characteristics, this is not expected to be relevant to defence applications [P6, P15]. Given the vast range of equipment and platforms operating in the limited spectrum allocated to military use, the EM environment will be heterogeneous. Furthermore, with the introduction of adaptive technologies, it may not be clear which devices should be considered ‘primary’, i.e., have priority access, and which are secondary and must yield to other users. Note, however, that it is believed that systems may be considered ‘cognitive’ without incorporating dynamic spectrum access.

In military applications, it is believed that the idea of a single cognitive radio has little relevance. Rather, the unit of interest is a radio network, where the network may consist of two or more radios, and may or may not incorporate relaying and multiple hops. The concept of cognition can therefore be extended from just the radio to the network itself. This means that the radio and network parameters, e.g., power, waveform, routing, frequency and protocols, should be adapted in response to observations and available information such as operating environment, user requirements, capabilities and policies, with the end objective of supporting mission effectiveness, including connectivity, throughput, robustness and security.

Cognitive radio networks are of particular interest for tactical environments, where radio nodes and networks may gather and share information and make autonomous decisions about their own operation to provide the desired service, taking into account the needs of other spectrum users. This autonomy will remove or reduce the burden of radio and network control from the user, and improve overall mission support.

2.3.1 Relevant defence R&D

The DARPA neXt Generation (XG) Program [G46] was the first major defence R&D program to incorporate DSA. Its objectives were to develop the critical technologies for enabling DSA for military use. The conclusion of the program was a successful, but limited, demonstration of a small mobile network adapting its frequency in response to conflicts with other emitters. The concepts developed within the XG program have been extended into continuing programs such as the Wireless Adaptable Network Node, part of the Wireless Network after Next (WNaN) program [G47]. In addition, in 2007 a Navy SBIR was issued to Shared Spectrum Inc., which undertook the development of the spectrum sensor capability within the XG program, to investigate the benefits of DSA within the JTRS radio.

Although the XG Program did demonstrate the feasibility of frequency agile mobile radio networks, it may have raised expectations unrealistically, as many operational EM environments are much more congested than the test scenario. Furthermore, it is highly unlikely that in practice radios will be able to operate freely in any band. This is partly due to regulatory restrictions, and partly due to the limitations of the hardware and RF, which will not support efficient operation over very large frequency ranges.

The UK MoD has an active Spectrum Dominance program, run by DSTL, which is finding solutions to spectrum congestion by more active spectrum situational awareness and management than is involved in the conventional approach, but which does not rely on ‘cognition’ or sensing capability at the radio nodes themselves.

Other work within the international defence community includes the NATO Research Task Group, IST-077 / RTG-035 on “Cognitive Radio”, which started work in mid-2008. Canada is represented in this RTG. The group has agreed to focus on the dynamic coordination of radio networks from a coalition perspective, in particular to address the problem of spectrum scarcity, considering DSA as a possible, but not essential, feature.

There is a related collaboration proposed within the European Defence Agency: “Cognitive Radio for Dynamic Spectrum Management” (CORASMA). The purpose of this project is to develop a simulation platform for demonstrating the application of cognitive radio for military use.

The TTCP C3I TP6 (RF Communications) held a two-session workshop on Cognitive Radio in 2008, held in Washington and Ottawa, in May and October, respectively [P12]. This was chaired by Dr. Tricia Willink of CRC, and included participation from several major US participants in the advancement of cognitive radio technology as well as representatives from C3I TP8 (Networking and Communications Technology) and C3I TP11 (Information Assurance & Defensive Information Warfare).

3 Dynamic spectrum access

The aspect of cognitive radios that has generated the most attention and research interest is their potential capability to identify unused portions of the spectrum ('spectrum holes') and adjust their own parameters to operate in these regions. This attention has been encouraged by results such as those shown in Fig. 1, which demonstrate that only a small percentage of allocated spectrum is actually in use. Fig. 1 shows the power observed in the frequency range 20 MHz to 1200 MHz, averaged over a 24 hr period, measured in the lab at CRC. In this case, even though the whole frequency range is allocated, over 75% had an occupancy below -78 dBm, which was the limit of the measurement capability.

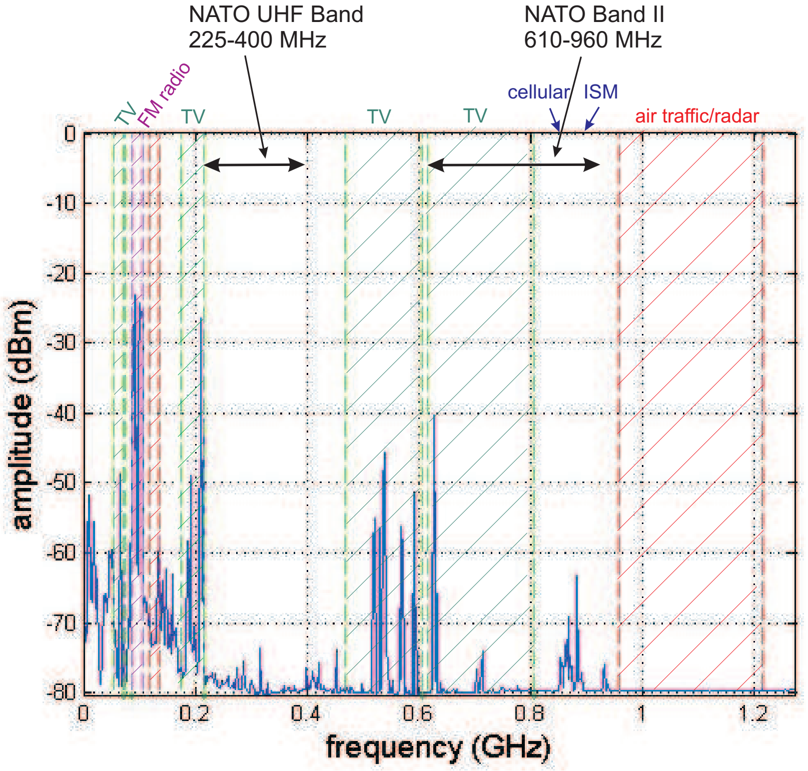


Figure 1: *Spectrum occupancy observation at CRC, averaged over 24 hrs.*

These types of measurements suggest a mode of operation that is illustrated in Fig. 2. Here, a cognitive radio device ('secondary user') moves around the spectrum, exploiting spectrum holes, and vacating spectrum when the allocated ('primary') user returns.

Illustrations such as that in Fig. 2 are common in the academic literature, e.g., [G48], but the most important feature, from a practical standpoint, is missing – *viz.*, the scales. As noted in Sec. 3.1, below, obtaining a sufficiently sensitive measurement about the availability of a certain frequency bandwidth (power scale) is challenging. However, it should be noted that the requirements for spectrum sensing accuracy are not likely to be as stringent for military

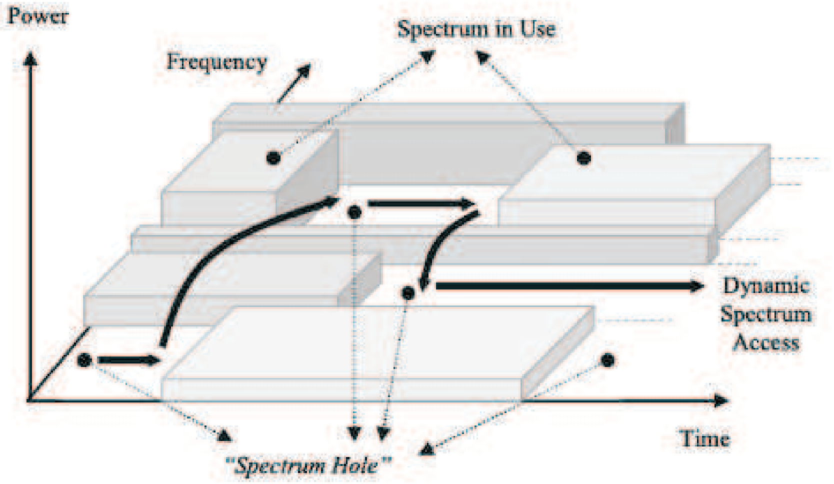


Figure 2: *Illustration of spectrum hole concept [G48].*

applications, when both the primary and secondary users are operated by a national or coalition force.

The lack of a timescale in Fig. 2 has led some researchers to suggest exploiting vacant TDMA slots, typically on the order of a few microseconds long. This is unrealistic for most communications systems due to the time required for identifying the spectrum hole, retuning the devices and exchanging control information. The demonstration of the DARPA XG program in 2006/7 showed that, for a network of six nodes, network reestablishment on a new frequency channel could be achieved in around 150 ms. The time required for a new node to identify and join the network was around 5 s [G49]. The overhead and time to identify an alternative frequency channel would increase in a congested EM environment. Also, the timescale and the temporal characteristics may become quite different in the future, as more dynamic and autonomous devices are in service.

Finally, the frequency scale in Fig. 2 is unlabelled – many researchers expect that a device would be readily retunable over a range of, say, 30 MHz to 3 GHz. This again is unrealistic. A single radio platform, a software defined radio, would require parallel RF chains, filtering capabilities and waveform specifications to cover the wide frequency range. As propagation characteristics vary considerably over this range, the device would be unable to support the same suite of applications over the same distances across the full frequency range. However, for military applications where the range of operation is limited by international treaties, these physical limitations are not likely to be a concern.

3.1 Spectrum sensing

The IEEE 802.22 WRAN standard in development (Sec. 2.2.1) illustrates the challenges in sensing spectrum occupancy for dynamic spectrum access. To ensure interference to licensed users is maintained below the accepted threshold, the current IEEE 802.22 proposal requires the base terminal and access points to sense the presence of analog and digital TV signals, as well as wireless microphones. The receiver must be able to detect, with a probability of 0.9, the presence of a digital TV signal at -116 dBm (6 MHz bandwidth), analog TV at -94 dBm (6 MHz bandwidth) and wireless microphones at -107 dBm (200 kHz bandwidth). Note that in Fig. 1, the measurement resolution was limited to approximately -78 dBm using good quality lab instrumentation. Detection of channel occupancy must occur within 2 s of the start of transmission by the licenced user. To enable, but not guarantee, the required sensitivity, all the nodes must be equipped with sensing antennas located outdoors, clear of obstructions, at least 10 m above ground level [G50].

The detection of licenced signals in the TV bands is challenging, but aided by the fact that the characteristics of those signals are known, in particular their pilot signals. The sensing process focusses on those known characteristics, and is aided by a mandatory database service which provides additional information about the operation of licenced services.

3.2 Challenges in autonomous DSA

The application of dynamic spectrum access in tactical-type operations is particularly difficult due to the heterogenous nature of the EM environment. Unlike for the IEEE 802.22 WRAN, the other users of the bands of interest include sensors and surveillance as well as a wide variety of communications devices and platforms. Detecting the presence of these other signals is more challenging than detecting a TV signal because of their unknown characteristics. However, it may be that these other users have more interference tolerance than in the TV case, in which case the sensing sensitivity required may be easier to achieve. This is an area that will require further study as the technology advances, as the impact of making the wrong sensing decision, i.e., interference, on the other users must be understood.

Mobility is the source of additional challenges. The detection of signals whose statistics are changing is harder to analyse, and therefore establishing appropriate thresholds for missing signals vs. false detection is much less precise. Uncertainties such as Doppler shift and noise power as well as quantisation within the detector introduce SNR walls [G51] which limit the detection capability even if the sensing interval is very long.

DSA introduces new vulnerabilities into the system. In particular, a radio network that is instructed to avoid interference with other spectrum users will change frequency whenever it detects the presence of another signal. The network must then identify a new spectrum hole and reestablish itself there. The system is therefore susceptible to intentional or unintentional spectrum occupancy attacks, causing it to reestablish continually, failing to achieve information transfer. Thus, military DSA capabilities should incorporate some system of priority to determine when to change frequency. This is not a requirement for purely secondary systems such as IEEE 802.22 WRAN.

Current regulations and international treaties do not allow radio devices to operate at all frequencies. The national allocations specify the type of user allowed in any spectral region as well as limits on the emission power. Although some national spectrum regulators are supportive of R&D to make more efficient use of the spectral resource, as the technology advances trust must be built that order can be maintained.

4 Technical contributions

4.1 Approach

The area of cognitive radio networking is considered to be more promising than when this project was proposed. However, some technical aspects are very challenging, requiring novel and cross-disciplinary approaches, and the scope of the overall concept is greater than originally envisioned.

The work was focussed on two key cognitive behaviours: learning and decision making. In real operating environments, particularly mobile networks in congested spectrum, learning intervals must be limited to very short durations, using methods such as iterative techniques. Decision-making requires characterisation of a complex, multidimensional tradespace.

Detailed descriptions of the technical achievements are not provided here. Summaries of the directions taken and results achieved are given below, and their relevance and interest to the overall project objectives are described. More detail on the topics can be found in the references cited.

4.2 Channel characterisations

As radio terminals operate either on the move, or in a mobile environment, the specific characteristics of the propagation conditions vary. The research team on this project has recognised expertise in the characterisation of the propagation and the impact that local conditions have on the performance of radio systems.

There is a lot of theoretical analysis in the literature, as well as algorithms and techniques that have been optimised and evaluated for idealised channel conditions. These idealised conditions are effectively an average over very many locations, and are commonly considered to be ‘typical’. In fact, the propagation conditions affecting signal transmission in any specific location can be very different from the average. As the radio terminals move, then, their performance can vary significantly and rapidly. In legacy equipment, this has been accommodated by ‘backing-off’ the radio capabilities, but the aim of cognitive radio networks is to operate closer to the optimal to achieve higher throughput and spectral efficiency without sacrificing robustness.

To understand the potential for advanced techniques in real operating environments, it is necessary to consider more realistic channel conditions. Within this project, the CRC MIMO channel sounder, developed jointly between CRC and DRDC research projects over the past few years, has been used to support investigations of the impact of real channel conditions on potential capabilities of cognitive radio networks. The sounder supports eight transmitter elements and eight receiver elements, and can be used in a fully mobile environment. The sounder was described in [G52] and in more detail in [G53].

4.2.1 Spatial and temporal channel stability

In this project, one of the original questions posed was whether the radios could take advantage of knowledge of their specific location, for example, using a GPS receiver, and exploit this to achieve the best performance in terms of robustness and spectral efficiency. This is related to the learning objective of cognition: can the radio devices learn that in a specific location, they can use the same set of parameters that were used the last time they were in the same location? An associated question is whether prediction can assist the selection process, i.e., whether parameters optimised at one time instant can reliably be used to predict nearly optimal parameters at the next.

When a radio receiver moves through a complex environment such as an urban area, delayed versions (called multipath components) of the transmitted signal are received from different angles, as the transmitted signal is reflected from surfaces and propagated around corners. It has been observed in prior work that a small number of these multipath components tends to dominate the received signal. As the position of the vehicle changes, the angles at which the multipath components arrive change. Furthermore, components may be lost or added as the vehicle moves relative to fixed reflecting objects such as buildings. The combination of the multipath components at the receiver therefore changes with time, or equivalently, with location. This means that the statistics of the signal, in particular, the mean and variance, may change as the vehicle moves.

A new technique for the characterisation of time-series of observations of mobile radio channels was developed [P1, P7], to determine whether the statistics of the time-series have changed significantly over a short interval. The application of this technique to measured data (using both single and multiple element antenna data sets) demonstrated that real channels are highly nonstationary. For measurement obtained in downtown Ottawa, up to half of intervals of 4 m did not display consistent channel statistics.

As an example to put this into context, the Enhanced Position Location Reporting System (EPLRS) uses a TDMA structure with timeslots of length 1.95 ms and 128 timeslots (250 ms) per frame [G54]. Blocks of 256 frames form epochs, which are the units of network periodicity. Each radio is assigned at least one timeslot per epoch, but more usually, one per frame. The nonstationarity analyses mean that the channel characteristics observed in the same timeslot in over three consecutive frames are statistically similar only about half the time. Thus, if the radio were well-tuned for high performance in one frame, those radio parameters may not be applicable in the subsequent frame. From epoch to epoch, the parameters could be significantly different.

These results also indicate that the sensitivity to the specifics of the local environment means that it is not practical for the radio to ‘learn’ which parameters are optimal in a given location. If the trajectory of the mobile terminal, or of other objects in the environment, e.g., other vehicles in the convoy, varies by only a couple of metres, the channel characteristics may be markedly different. This indicates the need for advanced techniques that can respond quickly to immediate changes in their own environments, rather than building on knowledge from prior experience.

The results obtained from applying the nonstationarity analysis to the measured data make evident additional challenges that have been overlooked in conventional signal processing evaluation. In particular, the interval of consistent statistics is often so short that it is not possible to generate valid estimates of certain fundamental properties of the channel, particularly for the case of MIMO channels, see [G55]. Furthermore, when estimates have been obtained, they are applicable for very short intervals. This may have a significant impact on the performance of systems, and points to the need to consider channel variation to develop suitably robust signal processing techniques.

This aspect of the project has re-emphasised the importance of understanding the propagation environment and evaluating the impact it has on the expected performance of radio systems. Advanced techniques that rely on optimisation alone for adaptive and cognitive radio networks may not provide adequate robustness in real operating environments.

4.2.2 Multi-node space-time channel measurements

As discussed above, tactical communications systems will need to operate in a networked configuration, however, current channel models support only single links, between pairs of radio nodes. Network channel models, where used, typically assume the pairwise links are independent. In some cases, for example, for spectrum sensing, a correlation factor is applied – although mathematically useful, this is an average model of observations, and is not representative of any specific location.

As noted above, for high performance radio systems, it is necessary to have a good understanding of the channel characteristics. For example, to develop and evaluate adaptive network capabilities, models of realistic mobile multi-node environments are required.

The CRC MIMO channel sounder was modified to provide two transmitter nodes and two receiver nodes, each supporting four parallel RF chains. The four nodes can be moved independently, and remain synchronised with sufficient accuracy to extract the channel responses among all pairs of transmit and receive antennas.

The modified sounder configuration has been tested around the CRC/DRDC Ottawa campus, as illustrated in Fig. 3. This test campaign demonstrated the capability of the network sounding configuration. No other such MIMO sounding equipment is known to exist.

This channel measurement and characterisation capability enables future investigation of

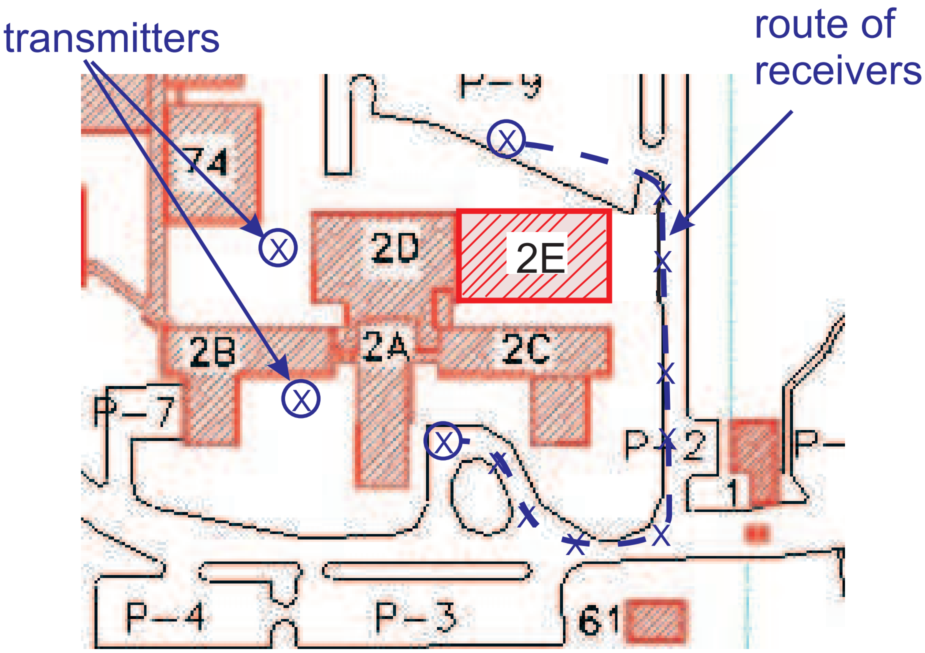


Figure 3: *Multi-node measurement test on CRC/DRDC Ottawa campus. Two receivers were moved along receiver route, two transmitters remained in same locations.*

the impact the conditions local to each transmitter have on the received signal at different locations, by making simultaneous measurements. Similarly, the impact of local conditions at one receiver on signals emitted from two different transmitters can be evaluated.

This capability will continue to be exploited, with more advanced measurement campaigns and detailed data analysis and channel characterisation, to support the development of improved network models for adaptive networking and for distributed spectrum sensing.

4.3 Dynamic spectrum access

Dynamic spectrum access is a very active area in the R&D community, therefore this research project did not make it a focus. However, with the insights that have been obtained, particular aspects have been identified and form part of ongoing work.

4.3.1 Spectrum segmentation

As discussed in Sec. 3, DSA relies on reliable detection of spectrum holes, i.e., regions of the spectrum that are unused in a given location. While highly sensitive techniques rely on knowledge of signal characteristics, it is believed that the military environment will not require such stringent detection thresholds.

A spectrum segmentation method has been developed that is suitable for the type of heterogenous EM environments expected. The approaches uses a ‘reversible jump Bayesian Markov chain Monte Carlo’ method [P8, P24]. The observed power spectrum is modelled as a noisy estimate of a piece-wise constant function, in which signals may have any bandwidth or received power. An iterative statistical search is performed to identify the signal band edges and heights, as illustrated in Fig. 4. This technique outperforms other known methods.

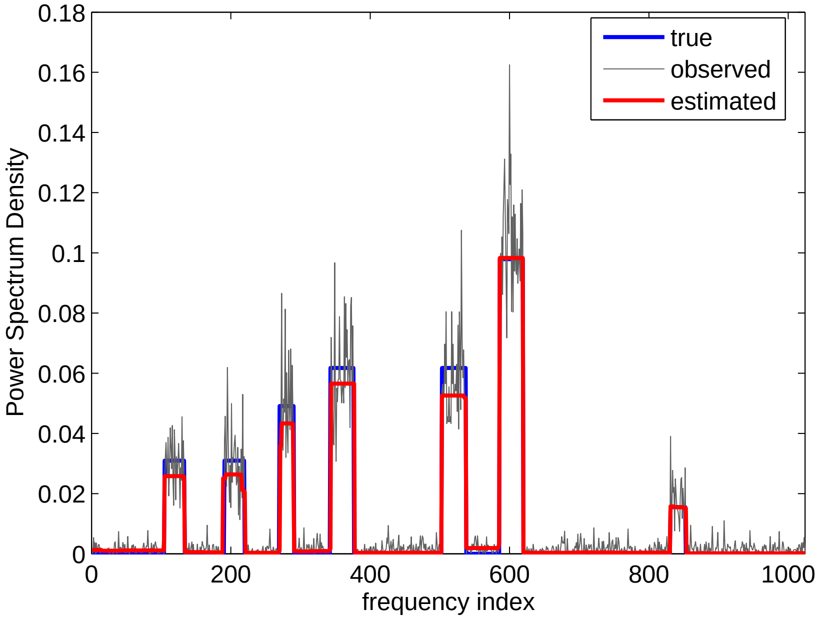


Figure 4: *Estimated spectrum occupancy extracted from a noisy observation of the power spectrum, using the reversible jump Bayesian Markov chain Monte Carlo method.*

When no *a priori* information is available about the spectrum occupancy, the iterative process required to achieve results such as those shown in Fig. 4 is quite lengthy. However, it is believed that due to the learning capability inherent in the iterations, this will be an efficient and accurate method to track changes in the observed power spectrum as emitters turn on and off, or move relative to the sensor.

4.3.2 Collaborative spectrum sensing

For radio networks, there are multiple nodes that could act as spectrum sensors, so it is natural to ask whether the node observations might be combined to provide more sensitive spectrum sensing. In particular, having multiple observations helps to avoid the “hidden node” problem, whereby the primary transmitter is shadowed from the sensor node. With multiple sensors, the probability that all the nodes are shadowed should be small.

Exchanging observations among sensor nodes, or between them and a fusion centre, has costs, including latency, power use and spectral occupancy, which must be balanced against the gains. This is an important problem which has not been adequately dealt with in the literature. Realistic models of the network radio characteristics do not exist, and the impact of effects such as correlated observations is not well understood. Work in this area is ongoing.

4.3.3 Dynamic spectrum management

The concept of a radio environment map (REM) was discussed in [G56, Ch. 11], as a method for supporting cognitive network operation. The REM concept proposed there was a database containing local information such as propagation characteristics, spectrum profile, location-specific operating policies, etc. The spectrum profile would include both archival information achieved by data mining and current information obtained by detection.

In 2008, a TTCP Workshop was held jointly by EWS AG5 (EW and Network Centric Operations) and C3I AG2 (Spectrum Research Priorities) to consider the generation and sharing of spectrum situational awareness (SSA) through the implementation of an RF common operating picture (RFCOP) [P13]. The RFCOP is similar in concept to the REM, using the other operational COPs as sources to identify platforms with RF emitters. Current information would also be provided by EM sensors. The RFCOP is not intended to deal with propagation aspects, but rather to identify RF sources and possible spectrum opportunities.

As part of the Spectrum Dominance program in the UK, Logica Inc. has developed a defence spectrum management capability, AURORA [G57], that uses knowledge of asset locations and their RF capabilities to identify high risk areas of spectrum. This aids spectrum managers in focussing their efforts on problem areas, spectrally and geographically.

There are many challenges to overcome to achieve a near-real-time spectrum environment map – the main ones of interest in this project are the cost, latency and overhead associated with sensing the EM environment, sharing and combining the observations, as well as the impact of the inevitable sensing inaccuracies and delays on the utility of the technology. Work addressing these concerns was started under the TIF project, and is continuing under the subsequent ARP.

4.4 Autonomous network functions

To understand the challenges, feasibility and trade-offs required in implementing a cognitive radio network, a number of smaller problems were investigated to gain insight. The network functions considered were related to network formation, specifically node identification and clustering. An approach to spectrum sharing among nodes in a network was also considered.

4.4.1 Rendezvous

The rendezvous problem envisions a scenario in which radio nodes aim to connect with each other, with minimal shared *a priori* information. For the case of cognitive radios, each node is assumed to sense its local EM environment and identify available frequencies; it will then try to connect with other nodes on one of those frequencies. In congested and challenging propagation environments, e.g., urban areas, it is likely that nodes will have different observations about spectrum occupancy. To connect, two nodes must be tuned to the same frequency at the same time. With no common control channel, the nodes must transmit and listen on the set of available frequencies until they coincide.

The challenge of connecting cognitive radio devices into a network with no infrastructure or control channel is a component of the vision of autonomous, network-forming radios. There are a couple of situations where this might realistically be a concern for military systems. First, in the future, cheap, disposable spectrum sensing devices might be deployed in the battlespace to provide real-time spectrum monitoring. These devices would have to be able to form their own networks without knowing the location or number of their peers. Second, if the behaviour of cognitive radio nodes is not well-controlled, it is possible that one or more might be disconnected from their networks through intentional or unintentional spectral action. In this case, the node must be able to resynchronise with its peers without the benefit of a planned frequency for reestablishing contact.

The focus of the work has been to understand the latency involved in establishing a network without a control channel. The case of two nodes was considered initially. It was noted that the main challenges are the different spectrum observations at different nodes (spectrum heterogeneity) and that the nodes have no common timing (asynchronicity). An important consideration is whether rendezvous can be guaranteed, and if not, what the probability is that rendezvous will be achieved within a specific time.

The investigation has led to a modified probabilistic wait/search strategy based on [G58], the performance of which was evaluated and compared to all other known unaided rendezvous techniques. The investigation considered some more practical physical conditions than in other work, to take into account that the spectrum observations may be correlated. Models of this correlation are not available, but might be achievable using the CRC MIMO sounder in its multi-node configuration (Sec. 4.2.2).

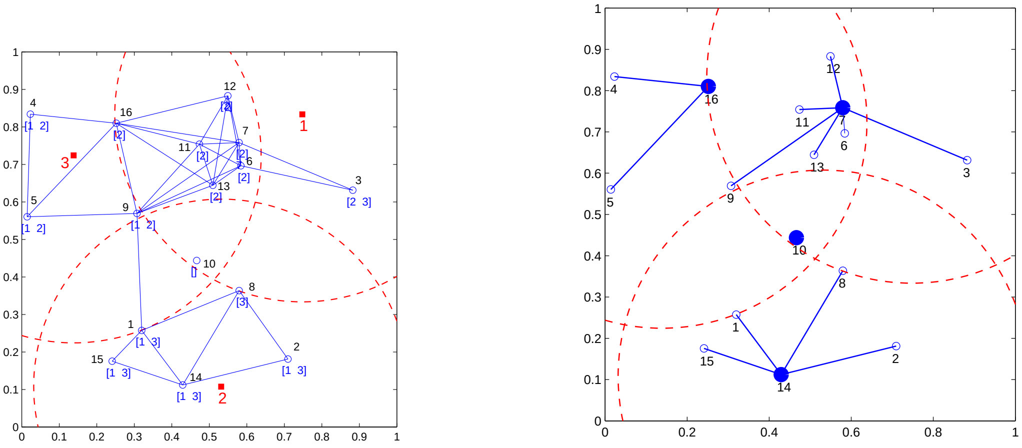
This area of study has illustrated the extreme challenge in achieving rendezvous even with just two nodes. The problem of multiple nodes is under consideration, but it is clear that relying on this type of autonomous behaviour is a potential barrier to achieving robust and reliable networks.

4.4.2 Cluster formation

To control the overhead in large networks, the nodes may be formed into clusters, each with a clusterhead that is responsible for communicating with other clusterheads in the network. This improves the efficiency of network functions such as routing and multicasting. In a dynamic environment, this structure also limits the impact of changes such as spectrum agility in response to local interference.

The organisation of the nodes into clusters should not require user oversight, but can be achieved autonomously in accordance with the application requirements, network characteristics and EM environment. In this project, a novel approach to cluster formation was proposed using the affinity-propagation algorithm, which was introduced recently and has been used for tasks such as facial image classification [G59]. In this method, nodes exchange messages with their neighbours to share information about similarities and to determine their relative suitability as clusterheads.

Fig. 5(a) shows 16 radio nodes randomly located around three primary emitters, operating on different frequencies. The dotted lines represent the extent of the primary signals; pairs of nodes that have a common spectrum hole are joined by a solid line. After the clustering process, there are four clusters, one of which has only a single node (10) that does not share a common frequency with any of its neighbours.



(a) Connected secondary nodes. Channels available to secondaries are shown in brackets below the nodes. Primaries are shown as squares, secondaries as circles.

(b) Clustered secondary nodes. Clusterheads are shown as filled circles.

Figure 5: *The affinity propagation clustering algorithm applied to a cognitive radio network with 16 nodes, with 3 primary emitters.*

This affinity-propagation clustering algorithm has been demonstrated to produce a smaller number of clusters than other algorithms [P9, P2], which results in a more efficient network structure. Furthermore, the algorithm can be operated in a centralised manner, in which the information from each node is passed to a central node where the clustering algorithm is implemented, or in a decentralised fashion, in which the nodes only exchange information locally.

4.5 Spectrum sharing

The challenges of dynamic access were discussed in Sec. 3.2. An alternative to sensing and occupying spectrum holes is to adapt the transmitted waveforms to coexist in the same spectral bandwidth. Two approaches to this concept were addressed in this project, one from a practical perspective and one from a theoretical point-of-view.

4.5.1 Co-existence by spectral overlap

When a second radio transmits in a frequency band already occupied by a first radio, it causes interference to the receivers of both signals. In some cases, multiple signals can be designed to coexist, for example using direct-sequence spread spectrum (DSSS) waveforms (or equivalently, code-division multiple access (CDMA) signals) but this coexistence comes at a cost in rate to all users.

In this study, a simulation framework was established to investigate the relative importance of different parts of the signal spectrum. It was found that for different types of modulation the central part of the occupied bandwidth is the most susceptible to interference. When interference occurs on the band edges, the performance degradation may not be severe if the overlap is less than about 25%.

This study was undertaken as a co-op student's work-term and final year project [P14, P32]. The results are sufficiently interesting that this study is continuing in more detail in ARP 15bx.

4.5.2 Co-existence by frequency sharing

Theoretical insight into the potential for coexistence of signals within the same spectral band can be gained by considering the 'iterative water filling' algorithm (IWFA). In the IWFA, multiple nodes use orthogonal frequency division multiplexing (OFDM) to transmit their information in a given bandwidth using many orthogonal tones. Each tone may be dedicated to a single node, or may be shared by multiple nodes, in which case the power allocated by each must be determined to allow only acceptable interference to other users. This determination is made in a distributed fashion, with each user deciding which tones to use and how much power to allocate based on their observations of the other users' signals.

As the computation process iterates, the users converge to an allocation that should achieve a large total data throughput.

A modification to the standard IWFA was developed in this work [P3], which provides robustness to the quantisation error in estimating the amount of noise and interference at each node. An interesting observation about the resulting algorithm, called robust IWFA, or RIWFA, is that even though the algorithm is distributed, the users unintentionally collaborate to achieve a high total throughput.

Although the RIWFA algorithm is unlikely to be practical in its current form in a real network, it does provide insight into the types of behaviour that will likely lead to a good solution to the coexistence problem. In particular, it provides insight into the conditions under which users can coexist efficiently vs. those where a frequency channel should be dedicated to a single transmitter.

4.6 Cooperative networks

Cooperation in radio networks is a mechanism for overcoming degraded links to provide robust and reliable communications among network nodes. Relay nodes assist the source node by forwarding messages, hence the destination node is presented with multiple signals received from different locations, providing spatial diversity. The costs of this approach include increased latency and reduced spectral efficiency, but this is offset by the reduced power requirements and smaller geographic range of spectrum occupancy.

4.6.1 Imperfect synchronisation

One of the areas that has previously been overlooked in the area of cooperative communications is the impact of imperfect synchronisation on the performance of the network. Synchronisation is required in time, frequency and phase – estimation errors in any of these parameters lead to reduced performance.

The investigation in this area has considered the quantification of the effects of synchronisation errors [P33]. The effects of timing jitter and frequency offset on the effective SNR were bounded; the effective SNR can be used to assess other performance metrics in the network.

Initial work on the extension of this analysis to multiple hops has begun, and is continuing under ARP 15bx.

4.6.2 Cooperative relaying protocol

A protocol for the case where there are multiple cooperating relays assisting the transmission of data from the source node to the destination was developed [P34]. The source and destination are assumed to have multiple antennas, while the simple relays have only a single antenna, and are capable only of amplifying-and-forwarding the signal they receive.

Most protocols for this class of problem require detailed channel state information to be fed back to the relays and source, but it is known from prior work that this is unrealistic, particularly when one or more of the nodes is mobile, because of estimation errors and feedback delays. In the proposed method, only phase information is fed back, resulting in less overhead and shorter delays. Currently, the phase information is assumed to be accurate – it is expected that future work in this area will consider the more realistic case of phase error due to estimation error, quantisation and delay.

4.6.3 Multi-node cooperation

Most work on cooperative relaying assumes that there is a single source passing information to a single destination. A more interesting problem, particularly from the point-of-view of efficient resource use, is that of multiple sources attempting to reach multiple destinations. Note that this is a similar problem to that addressed in Sec. 4.7.2, where sophisticated coding and resource optimisation have been applied.

When there are multiple relays cooperating, they can be viewed as a single array. Applying weights (amplitude and phase) to their forwarded signals makes them operate as a beamformer or adaptive array. The objective in this work is to determine the optimum weights that should be applied to the cooperating relays, to achieve a specified QoS and subject to power constraints [P35, P36].

Initial work in this area was undertaken in this project, dealing with the case of a single, common destination. The work is continuing under ARP 15bx.

4.7 Cross-layer considerations

In the late 1970s, in response to the increasing complexity of radio communications, an effort was initiated to define distinct layers of network architecture to simplify the design and implementation. The result was the Open System Interconnection reference (OSI) model [G60], Table 1. The layers describe functions that serve similar purposes, relying on the layer below to provide some defined service, and providing a higher service function to the layer above. The OSI model allows algorithms and protocols to be specified within a single layer, with limited and well-defined communication between adjacent layers.

The abstraction into layers is well established, and unlikely to change in the near term, but it is clearly the source of inefficiencies in the radio network. Each layer introduces overheads, which may contain duplicate information and reduce the effective spectral efficiency and increase power requirements, buffer occupancy and latency. Furthermore, the restrictions on communication among the layers mean that relevant information at one layer is not

Table 1: *OSI model [G60].*

layer	**data unit**	**function**
7 – Application	data	provides network access to user and provides interfaces, e.g., web browsers.
6 – Presentation	data	addresses information syntax and semantics; provides encoding, encryption and compression.
5 – Session	data	establishes, maintains and terminates connections between applications at host nodes, including synchronisation of data stream.
4 – Transport	segment	separates data stream into segments on transmission, ensures data messages are complete and ordered, and delivers messages to correct process on host on reception; may also provide error control.
3 – Network	packet	delivers packets from source to destination; adds logical addresses of sender and receiver; performs functions such as routing.
2 – Data link	frame	delivers frames from one node to the next in the route; divides packets into frames and adds addresses; incorporates sublayers media access control (MAC) and logical link control (LLC), which deals with frame synchronisation, flow and error control.
1 – Physical	bits	deals with interface to physical media, i.e., radio channel, including modulation and bit synchronisation.

available to another. For example, the radio environment information at Layer 1 is critical to making good routing decisions at Layer 3, but is not readily available.

In cognitive radio networks, the objective is to provide the required quality of service to support the application, which is defined in Layer 7, in such a way as to minimise the resources required. The resource use is largely defined by the parameters at Layers 1–3, including data rate (modulation, bandwidth), spectrum access and network routing. There may also be some impact of Layer 4, which introduces redundancy for error control, as well as the data compression function of Layer 6.

It is clear that the radio and network functions cannot be continue to be considered independent of one another if efficiency and QoS are to be maximised. Without eliminating the OSI layers, it becomes necessary to think in terms of cross-layer adaptation, optimisation and performance analysis. The term cross-layer is generally used to refer only to the lower layers, specifically Layers 1–3, herein.

4.7.1 Cross-layer trade-offs

For cognitive radio networks, efficiency and QoS should be achieved through the adaptation not just of the radio parameters such as modulation, error-correction coding and power, but also of higher layer parameters such as packet size and routing. This results in a multi-dimensional trade-space, which must be navigated to provide robust, reliable and efficient communications.

To investigate the cross-layer trade-off, a cooperative multihop radio network was considered, Fig. 6, in which relay nodes are able to assist the transmission of data from the source to destination. While using the relays provides diversity against poor propagation conditions and therefore may result in more reliable reception, it also requires additional transmit power and spectral occupancy, as well as introducing additional latency into the system.

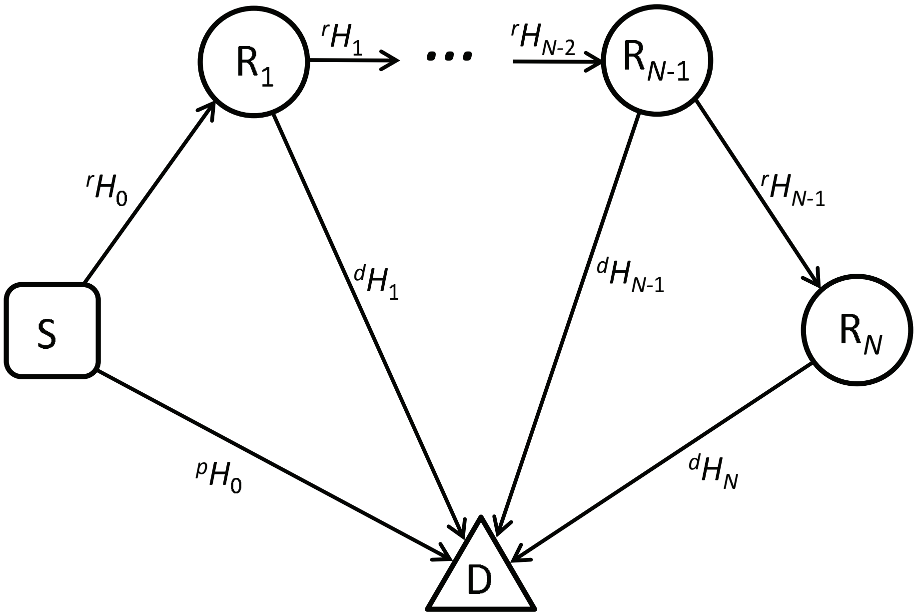


Figure 6: *Model of cooperative multihop radio network, where data is transmitted from source (S) to destination (D) with the help of up to N relays, R_i.*

An analytical framework for the evaluation of cooperative communications was developed and used to investigate the selection of cross-layer parameters for different propagation conditions between the nodes [P4, P10, P26]. The need to trade-off among packet length, modulation size and cooperative protocol to achieve the desired balance of data throughput, spectral occupancy and latency was illustrated, and it was seen that the network performance robustness is reduced significantly if the selection of parameters is poor.

4.7.2 Cross-layer optimisation

In a radio network, particularly in a challenging environment such as an urban area, links between some pairs of nodes may be disadvantaged by shadowing or distance. In this case, other nodes may be used as relays to forward messages. However, when multiple nodes have data to transmit to other nodes, there is a risk that the good links will become oversubscribed, leading to bottlenecks.

A theoretical analysis of this problem was undertaken to determine optimal cross-layer settings, in particular, routing and resource allocation (power and data rate) [P5]. Data for different destinations passing over the same link was transmitted simultaneously using superposition coding, and the optimisation algorithm assigned appropriate powers to each data stream.

Although theoretical, and not practical for realistic systems, this investigation provided insight into the challenges in supporting multiple users with finite resources, as well as hints for more practical approaches.

4.8 Performance evaluation

Performance evaluation of radio systems has conventionally been considered in terms of error rates at the bit or packet level, as with the analytical framework discussed in Sec. 4.7.1. But for a dynamic radio network, “performance” must be considered from a broader perspective. The requirements of the system include robustness, security and spectral efficiency as well as overall throughput [P11].

If some form of dynamic spectrum access is being used, the impact on other spectrum users, which may have vastly different performance requirements, must also be considered [P27, P28]. The cost of sensing spectrum, for example using a ‘look-through’ approach in which the transmissions are halted periodically to listen for other users, as well as the overheads required, for example to move the network nodes in a synchronised fashion to another frequency, must be considered.

Cognitive radio networks are complex systems, i.e., the behaviour of the whole is not necessarily predictable from the behaviour of the parts. This is exacerbated in the case where multiple cognitive radio networks coexist in the same spectral and geographical region. Complex systems are often considered in terms of their emergent behaviour, i.e., their end-state. But the cost of achieving that end-state must also be considered, as some behaviours, such as changing frequency, introduce vulnerabilities, risk loss of connectivity and increase overheads.

A thought experiment based on the Binni scenario developed within TTCP in the 1990s [G61] gave insight into approaches which might be appropriate for evaluating different types of behaviour [P29]. In particular, the dynamics of the environment appear to be one of the most important features that needs to be simulated [P11, P30]. This is being explored further within ARP 15bx, and has also influenced the direction taken within the NATO IST-077 RTG on Cognitive Radio.

5 Project outcomes

The area of cognitive radio networking is considered to be more promising than when this project was proposed. The flexibility to respond to advances in the external R&D community as well as within the project has meant that the direction was not as originally anticipated. This led to numerous technical advances (see Sec. 4) and far deeper insight into the complexities of the problems, which has provided direction for new and future R&D.

Scientifically, the cross-cutting nature of this technology will necessitate collaborative approaches among traditionally distinct research areas, in particular, radio, network and security. Aspects of data fusion, complex systems analysis and EW are also relevant. There is considerable progress to be made to understand the true potential of this technology. Key areas for future R&D are: effective spectrum sensing and dynamic access; performance evaluation (including modelling and simulation) of adaptive or cognitive radio networks; vulnerability assessment; and cross-layer optimisation to achieve spectrally efficient, robust communications. These are complicated by the realities of the propagation conditions, especially in mobile environments. The work in this project, and expertise developed through earlier R&D by the same group, provide a strong basis to address these challenges.

The opportunity arose during this project to participate in related international activities, including lectures presented on Cognitive Radio as part of the NATO IST-070 Lecture Series on Emerging Wireless Technologies, and a TTCP C3I TP6 Workshop on Cognitive Radio was chaired in 2008. Canadian participation in the ongoing NATO RTG on Cognitive Radio (IST-077) has also been influential.

This project has provided an excellent basis for the development of new technical and leadership skills, and the research group has benefited as a result. Through this project, CRC/DRDC has been established as a significant participant in the area of cognitive radio networks, in particular for military applications. Interaction with collaborators at Canadian universities has resulted in numerous new research activities, all focussed on aspects of this complex technology.

In addition to the expertise and insights generated within this project, a new Advanced Research Project, ARP 15bx, was initiated in April 2008, focussing on the spectrum-specific aspects arising from this project. The main objective of that ARP is to increase the capacity, robustness and flexibility of spectrum access through effective adaptive utilisation of spectrum and increasing the spectral efficiency of networked communications. It is anticipated that future project proposals will include more network-specific directions such as network science, adaptive protocol development and analysis, also using ‘cognitive’, or ‘context-aware’, principles.

6 Conclusions

Spectrum congestion is an issue that will impact the introduction of many new technologies by the CF over the coming decades. This is a significant concern for ADM(IM)/DIMTPS.

Spectrum availability is fundamental to many applications across the CF, but should not be taken for granted. New RF technologies should be designed to be spectrally-efficient, interference tolerant and capable of operating with reduced spectrum access. Spectrum flexibility, i.e., the capability to operate at different frequencies that may be assigned by a dynamic central manager or identified autonomously, should be built in to any type of equipment accessing the EM spectrum.

A core component of radio ‘cognition’, namely autonomous dynamic spectrum access, may assist with the better utilisation of the available spectrum. The capability for radio devices to find open spectrum and retune themselves is an attractive concept for dealing with congestion. However, this capability also introduces many challenges and vulnerabilities. Assessing the performance of this type of technology must take into account the “big picture”, e.g., the impact on other spectrum users, as well as the usual quality of service metrics.

Through this project, the term ‘context-aware’ has come to represent the desired technology more accurately. Within the R&D community, ‘cognitive radio’ has become focussed on dynamic spectrum access, but even in its broader form it suggests a degree of autonomous decision-making that may lead to unpredictable and potentially unstable conditions. Context-aware radio technology is a natural evolution of the adaptive radio technology that has been developed within the DRDC R&D program for several years. Ongoing R&D should help to develop trust in the ability of the technology to perform autonomous tasks.

The insights, and some of the specific technologies, arising from this project provide a strong direction for continued R&D both in more responsive spectrum management and in advanced adaptive radio technologies. Indeed, the follow-on ARP is focussed on specific aspects of efficient, dynamic access to the spectral resource.

The clear separation between the academic/commercial interest in this area (primarily IEEE 802.22 WRAN – the reuse of TV bands for consumer premise fixed networks) and the relevance to military use was surprising. While many of the hardware technologies, such as software-defined radio platforms and RF components, will be readily transferable, the concepts of operation appear to have diverged at an early stage.

It is believed that some aspects of this area, in particular the dynamic access to spectrum and the increased autonomy within radio networks, have the potential to be disruptive in providing the support for command and control capabilities that would otherwise not be possible.

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Annex A: Abbreviations and acronyms

CDMA	code division multiple access
DSA	dynamic spectrum access
DSSS	direct sequence spread spectrum
EM	electromagnetic
EPLRS	enhanced position location reporting system
FCC	Federal Communications Commission
JTRS	joint tactical radio system
MIMO	multi-input multi-output
OSI	open system interconnection reference model
QoS	quality of service
REM	radio environment map
RF	radio frequency
RFCOP	RF common operating picture
RIWFA	robust iterative water filling algorithm
SBIR	small business innovation research (US government program)
SNR	signal-to-noise ratio
SSA	spectrum situational awareness
TTCP	The Technical Cooperation Program (5-eyes R&D)
WANN	wireless adaptable network node
WNaN	wireless network after next
WRAN	wireless regional area network
XG	neXt Generation DARPA program

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The objective of the Technology Investment Fund project “Cognitive radio techniques for assured communications” was to investigate the potential of advanced radio devices to provide robust and reliable communications in highly congested spectral conditions. Cognitive radio is commonly associated with accessing spectrum that is allocated but currently unused, i.e., dynamic spectrum access. Commercial and academic interest has focussed on homogeneous spectrum reuse, mainly with static primary and secondary users. For defence applications, the environment is expected to be dynamic and heterogeneous, hence it is more appropriate to apply ‘cognition’ to respond to changes in its operating environment by appropriate adjustments of the radio and network parameters, not limited to operating frequency.

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