Cognitive Tactical Communication Networks

White Paper

Bittium

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Abstract

Cognitive Radio (CR) has been an intensive topic of research in recent years. Its main applications range from the utilization of TV white spaces to interoperability between large communication systems in all layers. Tactical communication systems that have to operate in hostile radio environments with interference, jamming and rapidly changing network topology share many common challenges with civilian cognitive radio. This has been recognized by defence organizations, and many related research activities have also targeted the utilization of cognition in tactical communications.

The Bittium Tactical Wireless IP Network (TAC WIN) is a mobile ad hoc network solution (MANET) with wireless broadband connectivity that can be deployed in any location. With the Bittium TAC WIN system, battle groups can create high-data-rate IP networks with wireless functionality as a backbone to support data and voice transmissions during operations. TAC WIN can be deployed as an independent network or as part of a larger operative network. Bittium TAC WIN combines the expertise of Bittium (Bittium) in physical air interface, including both waveform and radio channel knowledge, Software Defined Radio (SDR) implementation and exceptional versatility to support a great variety of applications and physical equipment connected to the same flexible and dynamic mobile ad hoc network with high-speed connections comparable to commercial Internet services.

1. Introduction

Cognitive radio (CR) systems obtain information about their environment to adjust their operation adaptively to provide required services to end users. Regarding spectrum use, future wireless systems equipped with cognitive radio capabilities could dynamically access new frequency bands, and at the same time protect higher-priority users on the same bands from harmful interference [1], [2]. For future mobile communication systems, cognitive radio techniques present a promising opportunity for cost-efficient access to spectrum bands to meet growing user demand. The emergence of CR techniques, especially in the terrestrial domain, has recently played a significant role in wireless research.

The focus in CR research has remained on terrestrial civilian networks, although activities such as Software and Cognitive Radio for European Defense (SCORED) addressed the same issues from the point of view of military communications. In addition to terrestrial applications such as utilizing the TV "white spaces" (the unused frequencies in between high-power TV-transmitters within the spectrum allocated for this application), cognitive radio has been proposed for, for example, satellite communications to allow more efficient spectrum utilization and frequency sharing between terrestrial and satellite systems. Multiple studies have been carried out in this field and it has been found that the key issue is to either avoid or manage the interference between systems sharing the spectrum, which is in fact quite close to the situation in which tactical communications systems are operated. In fact, cognitive radios, due to their inherent environment sensing and transmission adaptation capabilities, are perfect communication platforms to construct tactical communication systems.

2. Cognitive Radio

Future wireless communications will demand radio technologies providing significantly higher capacity, bit rates and flexibility than existing systems. In addition, wireless access should cover the entire population, including rural and distant areas.

New methods such as multicarrier techniques, use of multiple transmit and receive antennas (MIMO) and more efficient utilization of the radio channel have increased link throughput. On the other hand, system capacity can be achieved with small cells and coverage by building higher-power sectorized base stations with antennas high up on the masts. While the system peak-capacity can be handled by increasing the number of base stations, it will also increase network implementation and operating costs. The networks designed to handle the peak load also use the maximum amount of the available radio spectrum, which means radio frequencies will have to be reserved accordingly.

Cognitive Radio (CR) has been an active topic of research for some years now. CR technologies have been proposed to improve spectrum occupancy by exploiting the unused parts of the spectrum without interfering with primary users who have either higher priority or legacy rights [1], [2]. Cognitive radio provides a promising technique for wireless systems to resolve these issues, but it still has many challenges to overcome. Several competing definitions of cognitive radio can be found in the research domain. The official definition developed by ITU-R WP1B states that the cognitive radio system (CRS) is [3]:

"A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained."

Figure 1 shows a general cognitive cycle for characterizing the operations of CRS. According to the definition, CRS has the capabilities of obtaining knowledge, adjusting according to the knowledge and learning from the results. The definition is broad and detailed techniques for creating the CRS functionalities have not yet been defined.

The cognitive cycle was originally developed by John Boyd as the OODA loop (object, orient, decide, act) in battlefield operations. The idea of using and modifying the loop for wireless communication was invented by Joseph Mitola, the father of the concept of cognitive radio [1].

2.1 Spectrum awareness

Cognitive radios are aware of their environment, they learn from the environment and adapt to variations in the environment in real time. In many cases, awareness of the environment equals awareness of the radio spectrum obtained through its own active measurements or from external sources [4].

In active mode, CR devices sense the surrounding radio environment and adapt their transmissions based on the results of the measurements. Spectrum sensing techniques include, for example, energy detection, feature detection, and matched filter detection.

The performance of the sensing can be measured with the probability of a false alarm and the probability of missed detection, as illustrated in Figure 2.

Setting the correct threshold level is critical. If set too low, the probability of false alarms will increase. If set too high, the probability of missed detections increases, which increases interference for the primary user.

In passive mode, possible techniques are e.g. information sharing through databases and using a beacon approach where the primary user sends beacon signals advertising the

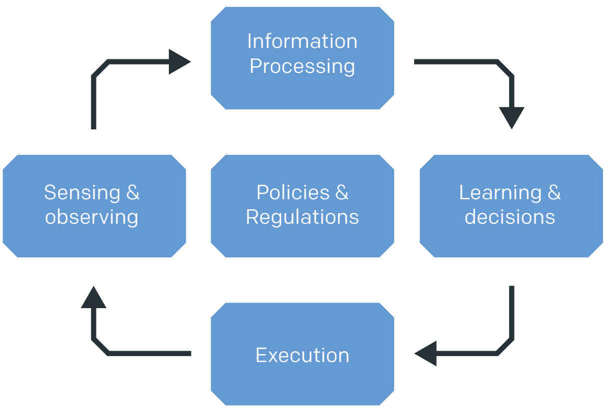

Figure 1: The cognitive cycle

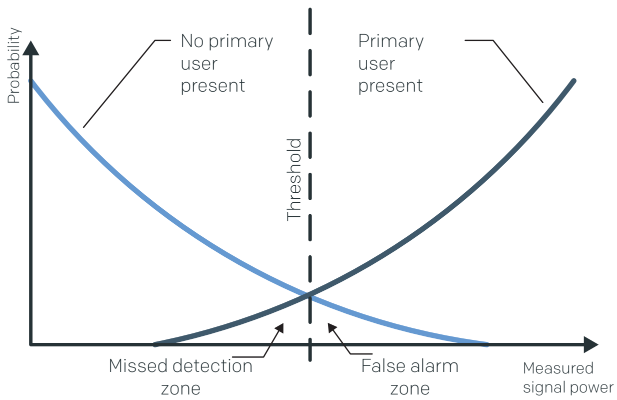

Figure 2: The probability of sensed signals

availability of certain licensed channels for secondary use. The passive mode works well in an environment where the spectrum allocation is controlled by a regulator. However, if the environment changes, the information in the databases may become obsolete. Therefore, in military communications the database approach well suited for civilian applications will not work as such.

2.1.1 Collaborative sensing

In addition to setting the right threshold for detection, the main problem in the sensing approach is the fact that a single node in the network may not be able to detect all other users based on its own spectrum measurements. Collaborative sensing, where the measurement results from different nodes are combined, may help to detect primary users much more reliably [5]. A primary user might not be seen by a single CR node due to a momentary bad channel condition, but a group of nodes will avoid this problem by introducing spatial diversity to the sensing. However, cooperation increases the amount of control and overhead information in a system.

The situation is illustrated in Figure 3. If nodes B, C and D were operating alone, they could not sense every node of the primary network as they are behind the hill and might come to the conclusion that the frequency is free. However, when transmitting, they might interfere with some of the primary receivers or they could be detected by the primary user. If collaborative sensing were used, nodes A and E would sense the presence of the primary network and share this knowledge with other users to avoid using the occupied frequencies.

In military communications applications, the spectrum information cannot be based on a public database, as there is no fixed frequency allocation information. A database may be used, but the information in the database must be actively obtained. As an individual receiver cannot detect signals reliably, information must be collected collaboratively, for example by using multiple nodes in the network as sensors. The information may then be stored in a single database and distributed throughout the network.

2.1.2 Response time

CR systems using different spectrum awareness methods have different response times. They require different amounts of time to detect spectrum possibilities and to start to exploit them. If there is a need to exploit short idle times in primary transmission, rapid methods based on active spectrum sensing are needed [4]. Energy detection methods are usually fast but not as reliable as feature detection methods, especially when the primary signal is not very strong. Feature detectors operate with lower signal-to-noise ratio (SNR) values than energy detectors since the latter do not exploit the information embedded in the received signal, whereas feature detectors do.

These methods can be also combined to achieve a tradeoff between speed and reliability. In [6], a CR system with dual-stage spectrum sensing is proposed. This approach combines coarse and fine sensing to meet speed and accuracy requirements. Firstly, an energy detection method takes a snapshot of the current spectrum use pattern over the whole band of interest and identifies the occupancy of each spectrum segment. Secondly, more sensitive time-domain feature detection methods may be applied.

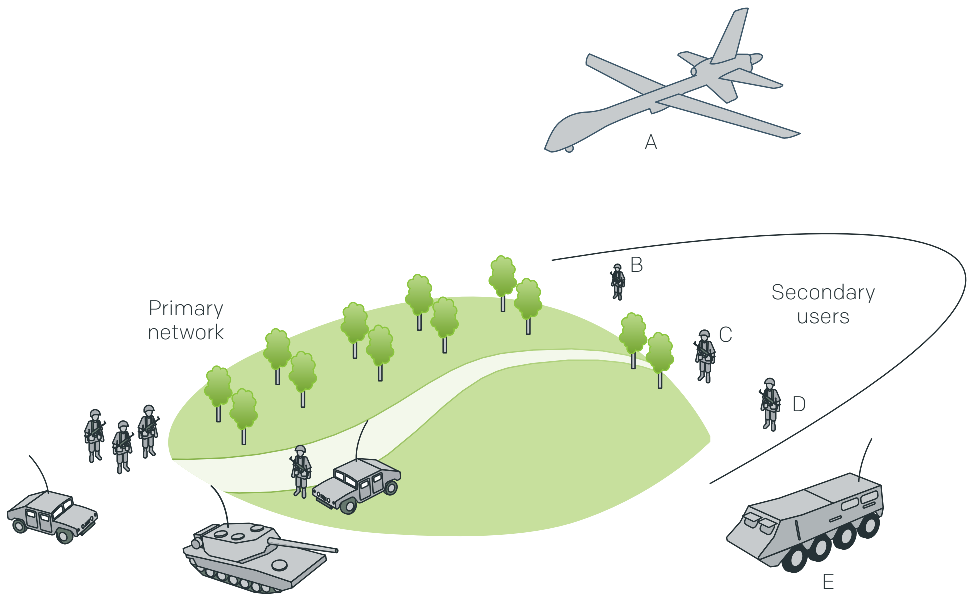

Figure 3: Example of collaborative sensing

2.2 Awareness of other resources

Spectrum awareness is not the only thing that can guide cognitive operations [7], [8]. Time, space, and energy are other possible radio resources to be aware of and guide operations. Spectrum sensing-based CR only knows the local situation around it. Cooperation and centralized passive awareness approaches can give global information from a wider area. Relaying and various MIMO methods can be used opportunistically to exploit spatial opportunities [7]. As an example, sensing combined with beamforming could give more accurate information about spectrum use in the vicinity. In addition to individual cognitive radio devices, the concept of cognitive networks has evolved [8]. The aim is to exploit cognitive principles all over wireless networks, including not only radio resources, but also network resources in order to enhance performance and the user experience.

In addition to taking immediate advantage of spectrum opportunities, a CR has the ability to learn from experience in order to make operations more efficient [9]. Historical information helps in both guiding the sensing as well as in selecting the best channels for control and data transmission [10]. Learning can reduce the sensing time, since previous knowledge can help to skip a set of channels that are very unlikely to be idle. It is not reasonable to waste resources on bands that cannot offer communication possibilities. Both short-term and long-term information can be efficiently used in this kind of scenario.

Even though the majority of cognitive radio research has focused on the primary-secondary scenario, cognitive techniques can also be used to improve the performance of the system itself. Cognition means awareness of all the air interfaces. The task could be to optimize the QoS for users based on the application requirements, availability of interfaces and their use in that region. The idea is that the network is both self-aware and self-adaptive and it recognizes where service is needed and instantly re-adjusts itself to deliver the right capacity, coverage and services to the right places. This principle also applies to tactical communication networks.

2.3 Resource management

A challenge in implementing a CRS is designing the algorithms that will take all the necessary information available, including the location of CR nodes, sensing information, the traffic patterns of different users, and database information, and then make decisions about where in the spectrum to operate at any given moment and how much power to use in that band, where to point the antenna beams and how to route data in between the nodes. In addition to the resource management algorithms, the next challenge is to implement the mechanism that controls all the resources throughout the network.

The two basic approaches in radio resource management are capacity maximization under interference constraints [2] and interference minimization by minimizing the transmission power [11]. Capacity maximization is a good choice when the performance of the secondary network is the main goal and optimization can be performed even at the cost of interfering with the primary user. In civilian applications, however, the most important aspect in designing resource management is to keep the interference with the primary network at the minimum level while serving the capacity and availability needs of the secondary network. The interference tolerance values of the primary system in both time and spatial domains are not allowed to be surpassed. The large challenge in interference management is the fact that cognitive radios cannot be aware of the precise locations of primary receivers and they cannot measure the effects of their transmissions on all possible receivers.

The interference temperature concept was designed to use measured interference information in interference management. One proposal was to use measurements from many fixed and mobile sites and integrate the data to create an overall power flux density map across a large area. The second approach was to use a separate sensor network over the operation area. However, the requirement for the density of the sensing devices is very high in order to map accurately the situation including shadowing effects. The Federal Communications Commission (FCC) actually abandoned the interference temperature concept since nobody could show effective ways to measure accurate interference information.

In practice, if the primary user does not tell the secondary system anything about the detected interference levels, which is the case with tactical communications in real in-the-field operations, the cognitive decision-making has to be based on clear rules. The rules will cover the frequency and radio parameter selection with transmission power limits and the link budget calculations as well as real measurements can be used to determine the possible signal levels for coexistence.

2.3.1 Cognitive engine

A cognitive engine (CE) [12] is an intelligent agent that manages the operation of the CR system and makes decisions and actions in order to achieve the specified goals. The CE may control both the methods of obtaining resources as well as their use. Artificial intelligence (AI) techniques such as genetic algorithms and neural networks have been proposed for cognitive engines. An advantage of an AI-based engine is that it can perform reasonably well even when the system model is not well known or the objective functions may change. On the other hand, a heuristic approach may lead to a very efficient solution when the requirements are well known and the system model is precise.

A rule-based system (RBS) approach is a natural way of encoding a human expert's knowledge in a narrow area into an automated system. Rules are usually expressed in the form of "IF conditions, THEN actions". The input is tested against the conditions, and the actions are taken if the conditions are satisfied. The simplicity of this approach makes it a very attractive choice. A radio can deduce actions for an input quickly using an RBS. The accuracy of this approach is heavily dependent on the completeness of the underlying rule base. A clear advantage of a rule-based approach is that there will not be unexpected outcomes because the possible outcomes are determined beforehand in the development of the rule base. A case-based reasoning system (CBS) starts from selecting the cases that are most relevant to the problem and then narrowing down the selected cases to a single case, and finally adapting this case to fit the current scenario. What makes CBS attractive is that it can develop as it operates and can thus operate in an unfamiliar environment.

One way to look at the use of the resources is to understand that adaptations in a CRS happen at different levels. Passive awareness may include use of databases, negotiations with primary users or use of common control channels in a network, among other things. In a dynamic frequency selection scenario, the node itself decides what channel to use for communication. Communicational cooperation mostly takes place at the PHY, MAC, and LINK layers [7]. Mutually interacting entities aim to enhance performance figures at link and network levels, and to improve the use of radio resources. Techniques include e.g. multi-hop techniques and cooperative diversity.

2.3.2 Radio resource management

Dynamic spectrum management (DSM) is closely related to transmitter power control. The DSM algorithm selects, based on the detected spectrum holes and the level of transmitted power, the modulation strategy that is appropriate to the surrounding radio environment. In addition, the algorithm selects favorable channels for transmission from among many possible ones. Beamforming can be used in directing the capacity to places where demand is densest. The algorithm will also adapt to time-varying conditions. The aim is to exploit efficiently the radio frequency (RF) spectrum and to assure reliable communication over a wireless channel.

In cellular communications, system capacity will become a major bottleneck as the capacity requirement is estimated to grow 1000 times higher within the next ten years. As the radio spectrum is becoming more and more crowded at the same time, improving spectral efficiency is a key factor. In addition to using advanced link techniques, the systems must also support low-frequency re-use schemes. To handle high interference levels, systems such as LTE and WiMAX use dynamic radio resource management, which includes dynamic frequency spectrum allocations of the resource blocks (RBs) as well as dynamic time-domain data packet scheduling. In principle, these techniques can also be applied to interference control in tactical communications systems, which also have to handle jamming in addition to interference.

The Radio resource management (RRM) operates at multiple protocol layers including, for example:

- QoS management and admission control (AC) in L3
- HARQ, dynamic scheduling and link adaptation in L2 (MAC layer)
- Control channel adaptation, CQI management and power control in L1 (PHY layer)

The principles of LTE link adaptation and packet scheduling are illustrated in Figure 4.

Scheduling aims to provide the needed resources to multiple users as efficiently as possible. In LTE, radio spectrum resources are allocated into a two-dimensional pattern in time and frequency domains, as depicted in Figure 5.

The instantaneous radio channel state for a single user is illustrated in Figure 5 by the depth of the color (the brighter the color is, the better the SNR). As the radio channels between the base station and each user do not correlate, it will be possible to schedule the resource blocks to each user in such a way that the users do not interfere with each other or with neighbouring cells, and to optimize system throughput. Similarly, the same principle can be applied to tactical communications to mitigate the effect of jamming.

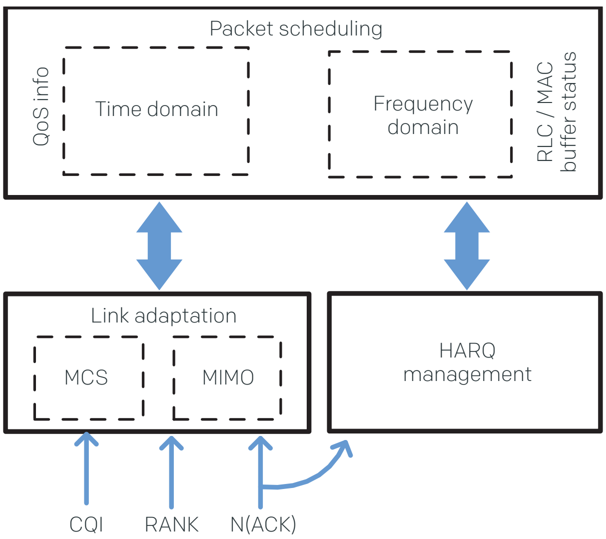

Figure 4: Principle of packet scheduling and link adaptation in LTE.

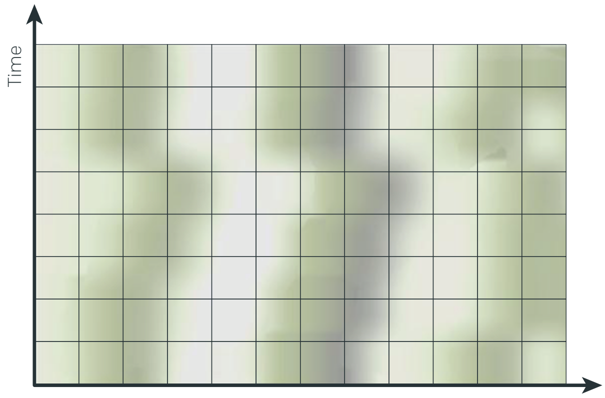

Figure 5: Example of a scheduling pattern

Time domain scheduling allocates resources to users based on their CQI (channel state/quality info) to serve those users that have a good enough SNR allowing reasonable throughput, and putting those with very poor SNR on hold for a moment. Time domain scheduling also takes into account the priority of each user.

Computer simulations and practical experiments have proved that a system deploying dynamic multi-dimensional scheduling is able to operate in a single frequency network and to provide the required capacity in addition to the quality of service. In addition, the system becomes more tolerant to jamming and interference from other systems. As the entire principle of multidimensional scheduling is based on radio channel characteristics, understanding and utilizing the radio channel becomes an essential factor, which applies to tactical military communications systems as well.

Figure 6 illustrates an example of simulated LTE-type cell throughput under interference from a satellite overlay network. The average SNR drops due to the interference, but the system does not become inoperative. Even users at the edges of the cell are able to maintain the connection with only minor degradation in link throughput.

It is obvious that tactical military communication systems can utilize the same principles currently deployed in commercial cellular systems. Close-range terrestrial or high-altitude jamming obviously causes a more severe situation, but a dynamic multidimensional RRM will help to minimize the impact of jamming. Modern wideband tactical communications systems, such as Bittium Tactical Wireless IP network (TAC WIN), that utilize waveforms based on multicarrier techniques provide excellent possibilities to deploy efficient radio resource management methods to improve the robustness and reliability of the system. With cognitive control, these systems will provide superior performance over conventional tactical communications systems.

2.3.3 Management of other resources

In a cognitive radio system, the topology formation is different from a conventional wireless network because of the dynamically changing environment [13]. The network must be capable of adapting to the environment and a fixed network topology is not easy to maintain, which leads to ad hoc data routing. The situation is quite similar with tactical communication systems, which have to deal with dynamic changes in the environment and adapt their functionality to the situation to establish and maintain communication. In addition to wireless resources, including not only the terrestrial link but also satellites and perhaps UAV-assisted radio links, the system should also be able to utilize wired connections. In most cases, the wired connection, if applicable, is still the most reliable method and provides the highest capacity for communications.

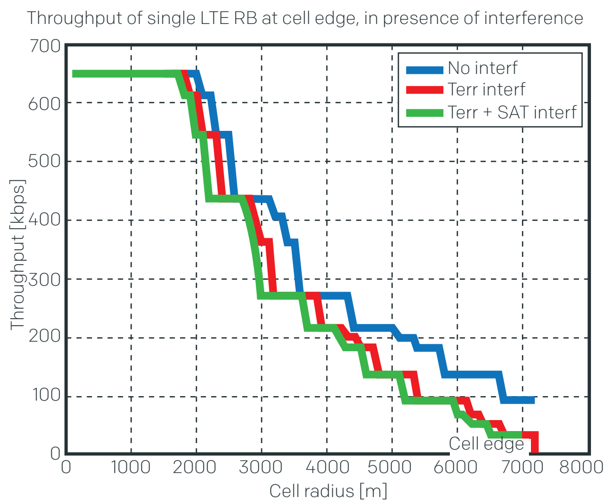

Figure 6: Example of LTE performance under interference

3. Cognition in Tactical Communications

Tactical communication networks relay orders and decisions from one command, person, or place to another within tactical forces. Cognitive radio systems and tactical communication networks actually face very similar challenges. They are both operated in a dynamically changing environment where interference and sudden changes in network configuration and radio parameters take place. Thus, deploying CR technologies in tactical communications is an attractive idea.

Early tactical communication systems deployed Morse code, which is a robust method of radio communication due to the very narrow signal bandwidth and the ability of the radio operator to extract the code even when buried under heavy interference. Since the introduction of voice transmission, available information bandwidth increased drastically but the connection also required a much higher signal-to-noise ratio. Today, modern radio communication systems are digital and the radio operator is no longer a part of the detection chain. Data rates have increased and communication systems transfer images, video and data, in addition to voice and data messages, between users, thus increasing the throughput and capacity requirements to a new level.

With traditional Combat Net Radios (CNR), it is rather challenging to guarantee a specific performance level for users. For example, radio operators are responsible for setting the right parameters on radio equipment. At minimum, dialing in the correct transmit/receive frequency has to be carried out. However, in order to establish the connection, the frequency and other parameters have to be agreed beforehand. In many cases, though, channel reservation has been stochastic. These problems were first limited through well-performed frequency planning, and later the introduction of wideband radios featuring automatic frequency allocation solved many issues with co-site interference. On the other hand, the lack of available frequencies has limited communication availability and link performance. In both cases, a major problem is the fixed resource allocation and poor system flexibility required to support link adaptation.

3.1 Current development

Modern tactical communication networks utilize adaptive radio interface capable of using multiple waveforms that provide the best performance depending on the situation and communications requirements. While multicarrier and MIMO techniques can be used to improve link throughput, cognitive radio offers new possibilities to further enhance the performance of a modern tactical communication system by introducing methods and mechanisms to avoid interference and interception, improve system-wide spectral efficiency and allow more flexible resource utilization. In addition to terrestrial wireless links, satellites, UAVs and wired connections are combined in a hybrid system (Figure 7).

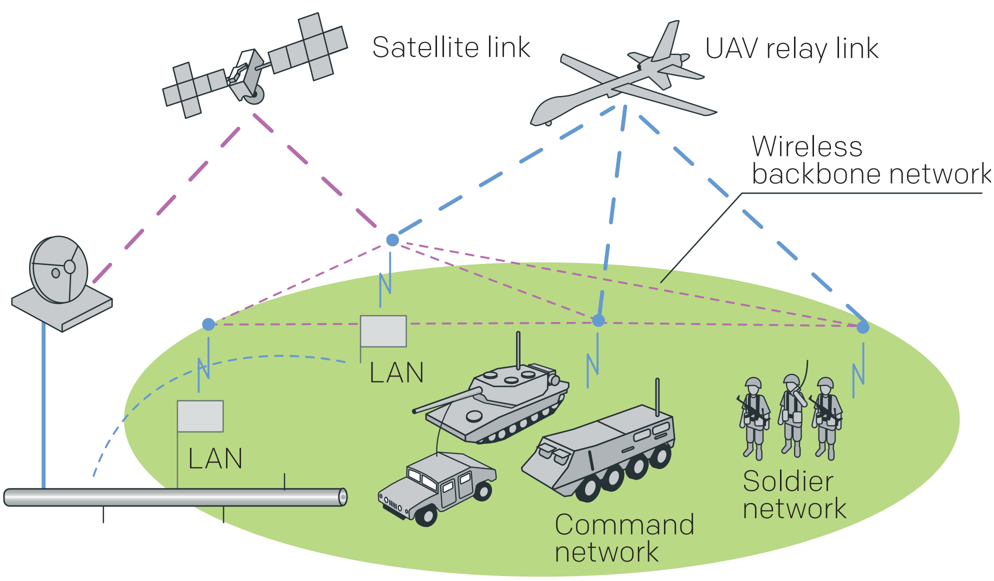

Figure 7: An example of a tactical communications scenario

In addition to multiple academic and industry-driven projects targeting common applications, research activities have been carried out to study the applicability of cognitive radio to military communications. As an example, Defense Advanced Research Projects Agency (DARPA) has launched several programs related to cognitive radio in the United States. DARPA's neXt Generation Program (XG) aims to develop both the enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms. In international operations, military forces face unique spectrum access issues in each country in which they operate. Coalition and allied operations are even more complex to manage and require extensive planning.

The neXt Generation Program is developing theoretical solutions for dynamic control of the spectrum, technologies and subsystems that enable reallocation of the spectrum and prototypes to demonstrate applicability to legacy and future military radio systems. The program plans to investigate new waveforms and medium access and control protocol technologies to construct an integrated system. The proposed goals are to develop, integrate, and evaluate the technology to enable equipment to automatically select spectrum and operating modes to both minimize disruption to existing users, and to ensure the operation of US systems.

In Europe, EU-funded projects such as ARAGORN and SENDORA, activities funded by the European Space Agency (ESA), such as ACROSS [14], and national projects and programs such as TRIAL, which is a program funded by the Finnish state aimed at developing concrete cognitive radio solutions, have been carried out and/or are ongoing. In addition, the European Defence Agency (EDA) has launched its own projects to support the development of CR and its applicability to military communications. An example of such an activity is the SCORED (Military Software-Defined Radio capabilities including applying Cognitive Radio-based Spectrum Management in the Security and Defence domains) project, in which many aspects of applying CR to various levels of military communications and the utilization of flexible radio spectrum management (FRSM) were studied.

3.2 The implementation of cognition

While a civilian cognitive network uses the available resources to enhance overall spectral efficiency and system capacity, a tactical cognitive network might utilize the same technologies to avoid jamming and interference, to build more robust radio links and to avoid interception. The anti-jamming capabilities of cognitive radios can be implemented in at least three different ways: at the hardware (e.g. directional antennas), physical (e.g. sensing, modulation and coding, beamforming), and network (e.g. routing) layers. CRs are capable of detecting jamming transmissions and hopping between many channels. The unique feature of the cognitive frequency-hopping system, when compared to a conventional frequency-hopping spread-spectrum system, is that the choice of next frequency band is made adaptively.

The same CR techniques could be applied in implementing smart jammers as well. The cognitive network could sense enemy transmissions and adapt the jamming signal accordingly to prevent enemy transmission. Both frequency and direction information could be used in smart jamming, applying the same techniques that were presented for anti-jamming purposes. In addition to the primary goals, improved overall system capacity, data rates and latency characteristics will be achieved. However, due to the differences in the nature of the applications, the implementations and their priorities are different.

3.2.1 Sensing

Compared to civilian cognitive radio, a tactical network faces a much more challenging situation. Any military communication system tries to emit as low an energy level as possible and uses methods to hide the signal or to make it otherwise difficult to detect, for example, by spreading the signal over a wide spectrum, which lowers the spectral energy density, or by using frequency hopping, which makes the signal hard to capture with scanning receivers. Therefore, it is obvious that collaborative sensing is the key to collecting reliable information from the surrounding radio environment.

In addition to external sensors, one possible solution to sensing the environment is to utilize the nodes of the communications network to act as sensors while not transmitting. By collecting information with multiple nodes and delivering the information for centralized data processing, a multi-dimensional picture of the radio spectrum combining, for example, time and frequency can be created (Figure 8).

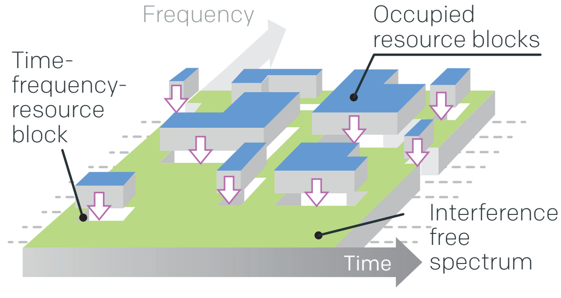

Figure 8: Example of two-dimensional spectrum view

3.2.2 Localization

The location of the signals presented in the radio spectrum is one important aspect. In addition to time and frequency, the geographical location of the signal source adds one more dimension to the picture. If the system is equipped with adaptive or even just directional antennas, possible interference can be avoided by beaming the antennas correctly. This also lowers the transmission power required to establish the radio link, including in cases where the other end uses an omnidirectional antenna, thus reducing the risk of interception.

Localization can be performed, for example, using the information about the direction of arrival of the signal. When combining this information from multiple sources, the position of the signal source can be calculated accurately. The radio channel, however, may introduce error to the DoA measurement. Although typically the strongest signal component is received directly from the source, sometimes the reflections may be stronger than the direct component. This error can be compensated for using TDoA (Time Difference of Arrival) measurements, which help to establish an independent estimate of the signal location which can be used to improve the accuracy of the DoA measurements. In addition, the signal component that arrives first typically comes directly from the signal source on the shortest path available, which is another parameter to be followed in order to enhance the localization accuracy. Utilizing this information, however, requires synchronization with the signal, which may be quite challenging if the waveform or its parameters are not known.

3.2.3 Adaptive antennas

In addition to selecting the operating frequency, antenna direction and other air interface parameters to optimize the radio link or the system performance, the network configuration and routing data in the network can utilize the cognitive information. As an example, if the sources of the signals presented in the local spectrum can be pinpointed on the map, it allows more efficient planning of the network configuration. The links can then be established for minimum interference and minimum probability of interception. Although a straight connection between two nodes might provide a good link, it may be better from a system capacity point of view to route the data via other nodes. In addition, there may be hostile forces between the nodes trying to detect or intercept the transmission, which is more difficult if the system can route the signal around the hostile areas utilizing directional antennas and short hops between nodes, both of which support using the minimum transmit power.

3.2.4 Routing

Although dynamic frequency sharing and controlling the radio interface parameters are typically first considered, the utilization of alternate communications channels is also an important form of cognition, especially in the case of critical applications such as military communications. In addition to awareness of the surrounding physical environment, a cognitive radio system should be aware of the available communication resources as well, and be able to utilize them.

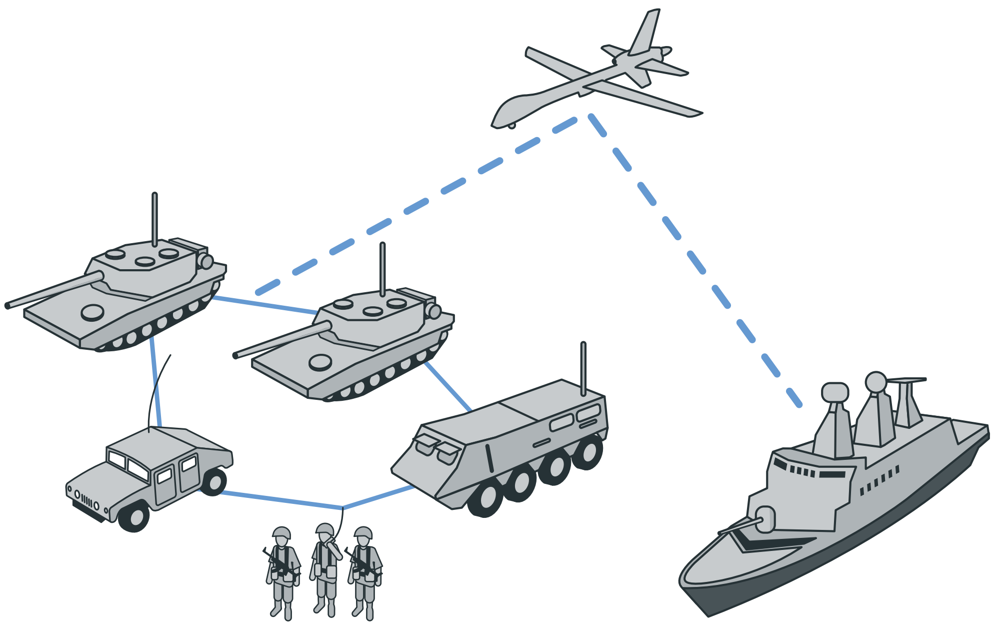

Figure 9: Example of extending coverage

In addition to redundant links built to enhance system reliability, alternate communication channels provided by, for example, a satellite link may allow communications links to be established in situations where the primary communications channel is not available. A satellite connection requires, in principle, connecting external satellite radio equipment to the system to provide the needed connectivity, which requires flexible and compatible interfaces. As another example, UAVs or other high-altitude platforms can be used to relay the backbone network signal to extend the radio coverage, as depicted in Figure 9.

One of the challenges related to using alternate communications routes is interoperability between systems. Today, IP-based packet traffic has become the de facto standard in most applications, which helps in routing data over different systems comprising wireless and wired sections. On the other hand, in order to utilize alternate routes and interoperability between systems, IP-compatible and flexible interfaces must be provided, which may not be the case with legacy tactical communication systems.

3.2.5 Decision-making

One of the most important aspects is to understand how overall cognition and its key elements can be implemented in an existing system. As there is no standard available for implementation of cognition in a tactical communication system, the implementation must be considered case by case. For example, what kind of approach is used to implement the cognitive engine, as there are at least two or three potential approaches available, including the centralized, distributed and the hybrid approaches.

The centralized approach has one single point where all decision-making considering the entire network takes place. On the contrary, the distributed approach has multiple points where decision-making takes place. The distributed approach provides much more computing power and is not so vulnerable to breaks in connections or the loss of critical nodes, and can utilize collaborative decision-making. On the other hand, keeping the entire system under control will be much more demanding if there is more than one decision maker that controls the network or parts of it. A solution to the problem is the hybrid approach, which combines characteristics of both the centralized and distributed approaches.

A hierarchical tactical communication system comprising several levels (e.g. squadron, platoon, etc.) that are connected to each other via gateways rather than allowing direct access between all individual nodes on different levels is one example in which a hybrid approach might provide the optimum solution. Although cognitive functionality will be distributed to all levels in the network, the actual decision-making is carried out locally in a single point, for example at the gateway. The information may be distributed to allow all nodes to be able to take the responsibility of the decision making if needed, e.g. in the case the current node in charge drops out of the network. Interested reader may look at some tactical network design aspects across the protocol stack from [15].

4. Bittium Tactical Wireless IP Network (TAC WIN)

Effective execution of operations requires mobile troops. The growing need for command and control data and situational awareness information on the battlefield call for efficient information sharing and communication at all levels. The ability to operate in hostile environments creates a need for well-connected nodes and flexible network management. Changes in network structure and connectivity from all nodes to other networks must be fulfilled with efficient routing protocols and different types of interface.

The Bittium Tactical Wireless IP Network (TAC WIN) is a complete solution to building a tactical communications mobile ad hoc network for vehicle and stationary applications. With TAC WIN, battle groups can create high-data-rate wireless IP networks as backbones to support C2 data transmission during operations. The flexibility to use the Bittium solution in different frequency bands and network topologies provides cost effectiveness, ease of use and efficiency in various tactical communication scenarios.

Supported by its wide connectivity options, TAC WIN can be deployed in any location joined to other systems or as a standalone network. It enables the formation of an independent IP network and is compatible with existing infrastructure. Being based on software-defined radio makes the product versatile, upgradeable and easy to adapt. It enables a flexible network solution with a high data rate and the automatic network configuration required by battle groups on the move. The product has both excellent performance and form factor, as both wireless connectivity and router functionality are integrated into a single product.

The Bittium Tactical Wireless IP Network is built with these basic components: the Tactical Router (Figure 10) and the Radio Head Unit (RHU, Figure 11). TACWIN provides flexible routing functionality and interfaces to establish the connection between nodes and to other systems using either wireless or cable/fibre communications. The wireless interface is provided by the router's integrated SDR baseband section that allows various military or commercial waveforms to be run, depending on the customer's requirements.

While the tactical router provides data routing and the IP connection, the RHU (Figure 11) performs the necessary front-end signal processing, digital-to-analog and analog-to-digital conversion and the analog signal processing, including low-noise, high-dynamic-range receiver circuitry, power amplification and co-site filtering to provide state-of-the-art RF performance in both transmit and receive directions. The Radio Head Unit is connected to the tactical router over an optical fibre connection to allow remote installation of the RHU.

The RHU can also be equipped with an auxiliary RX module to allow spectrum sensing in parallel with communicating. The major military frequency bands are supported with multiple variations of the RHU. In addition, customized variants can be provided on demand. The Radio Head Unit supports a variety of antenna types. For example, omnidirectional broadband antennas, adaptive mobile antenna solutions, sectorized fixed beam antennas and special high-gain directional antennas. Antenna types can be selected depending on the requirements of the application, for example based on network topology, distance between nodes, available masts and required setup

Figure 10: Bittium Tactical Router

Figure 11: The Radio Head Unit (RHU)

time. For the most demanding applications, sectorized and adaptive antenna solutions provide more gain, thus increasing link performance and allowing interference and interception to be avoided, as well as supporting cognition.

TAC WIN supports several network configurations and topologies. The Mobile Ad Hoc Network (MANET, Figure 12) configuration creates the most flexible network where all nodes are independent and can join and exit freely without the need to reconfigure the entire network. Typically, the antennas are omnidirectional and installed on a vehicle or on towers. The capacity of one node depends greatly on the number of nodes in the network and structure transformations. Network performance can be adjusted with node and data type prioritizations. The network topology is MESH.

4.1 Mobile Ad Hoc Network

While the MANET configuration provides the ultimate flexibility in setting up the network, the traditional point-to-point configuration used to build a link network provides the highest throughput between nodes (Figure 13). Two nodes can share full network capacity together. Typical installation uses directional antennas. If possible, a line-of-sight (LOS) connection is arranged to allow high operating frequencies, compact antennas and the lowest possible transmission power to be used, all of which contribute to providing a stable, interference-free link which cannot be detected easily.

As the point-to-point configuration provides the maximum performance between two nodes, it has typically been used in commercial radio transmission applications, for example, to replace expensive cable connections. In applications where multiple access is required, a typical solution is the point-to-multipoint configuration (Figure 14), in which one of the units acts as a base station while the other units are configured as mobile terminals that communicate via the base station. A typical example of the point-to-multipoint configuration is a cellular network such as the GSM network, where fixed base stations are deployed to provide wireless access for the surrounding mobile phones. In tactical communications, this structure allows the fixed core network connectivity and services to be distributed to tactical units. Sectorized and/or directional antennas are typically deployed in the base station, while the mobile terminals may use omnidirectional antennas. Network capacity will be shared between connected nodes, which set requirements to the resource allocation mechanisms.

The three different network configurations, MANET, point-to-point and point-to-multipoint, can be implemented with the Bittium tactical router using the selected waveform or waveforms.

In addition to the adaptive radio interface provided by TAC WIN waveforms, the ability to support multiple network configurations provides a major advantage, as it allows flexible

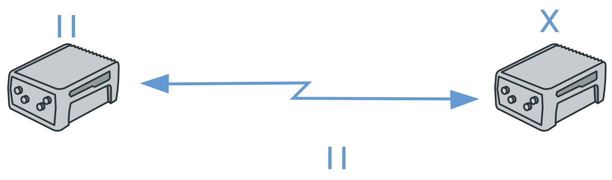

Figure 13: A point-to-point connection

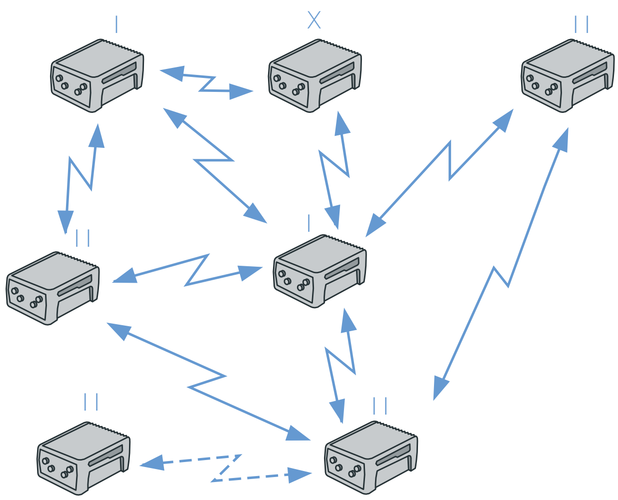

Figure 12: Mobile Ad Hoc Network (MANET)

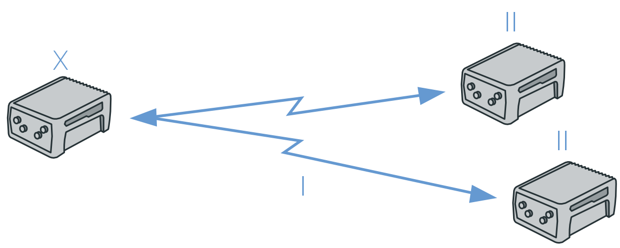

Figure 14: A point-to-multipoint connection

and adaptive network capacity sharing. This increases the real system-level throughput compared to fixed systems, as instantaneous capacity requirements vary drastically over time. In addition to flexible capacity allocation, the system can also be configured to guarantee a minimum throughput rate and service level to each user, which is essential in relaying time-critical messages.

4.2 Research and development

Bittium is currently developing technology and solutions that allow the deployment of cognitive radio functionality in practical applications. Following years of active work on MIMO and multicarrier technologies that provided a significant increase in the throughput of wireless links, cognitive radio is today one of the key technologies supporting the rapidly increasing requirements for system capacity. While spectrum resources are limited and bands have become more and more crowded, there is a need for methods that allow more efficient utilization of radio resources.

As part of its development work, Bittium is participating in many research activities. One of the most important activities is the Finnish national cognitive radio program TRIAL, which aims to bring research and the practical world closer together with the goal of arranging joint practical demonstrations where state-of-the-art cognitive radio technology is brought into real life in collaboration between research organizations and industry. The technology and results of the TRIAL program are being utilized in developing more advanced high-performance functionality for Bittium's products, such as TAC WIN. In addition, the TRIAL program supports Bittium's activities carried out in collaboration with the Finnish Defence Forces (FDF).

TAC WIN is designed to support future improvements with software upgrades. Cognitive functionality, increased throughput, new waveforms and many other features will only require a new software version to be deployed. It is expected that intelligent cognitive frequency allocation algorithms will have been field-tested and deployed by the mid 2010s, and advanced data capacity improvements by the end of the decade. Providing both smarter allocation of resources and advanced methods of using allocated resources, TAC WIN is ready for the increasing need for data and voice communication in operations, as well as supporting new demanding applications.

The FDF has launched a three-year technology programme, PVTO2013, which aims to develop novel technology and solutions to improve the performance of the tactical communication systems deployed by the FDF and to increase its electronic warfare capabilities.

The program comprises three parallel activities, one of which is solely focusing on tactical communications. This activity, led by Bittium, aims to develop air interface functionality comprising combat-proven LPD/LPI waveforms, adaptive high-mobility antennas and alternate communications techniques based on novel broadband HF solutions, all combined with cognitive network functionality. The ultimate goal of the activity is to bring the technology into real life and to demonstrate it with the TAC WIN solution during the program. The roadmap to the demonstration comprises research, computer simulations and engineering work utilizing advanced development tools such as the EBRACE-SDR platform (Figure 15), which combines the flexibility of SW simulation (such as Matlab) with real-time SDR performance, allowing engineers to quickly develop and evaluate the waveform functionality in the simulation while having the connection to the real radio interface from the simulation.

Figure 15: EBRACE SDR development platform

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