Challenges for Network Aspects of Cognitive Radio

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Abstract—**Cognitive Radio is often promoted to be a promising solution for the spectrum scarcity problem. Hence, a lot of research activities in both the civilian and the military world focus on introducing cognitive radio technology into modern networks. Besides the obvious changes in the radio architecture (sensing capability, cognitive engine), this combination of technologies also poses new challenges to existing protocols, like the support for Dynamic Spectrum Access. Moreover, the additionally gathered information about the spectrum environment can also be used to improve the quality of communication. In our paper, we focus on network aspects like Quality of Service or routing and identify challenges regarding their application in a cognitive radio system. We consider architectural features of infrastructure and ad hoc networks, and we analyse their influence on the control channel. The analysis is carried out in terms of specific requirements for military networks.**

Keywords-cognitive radio; network; infrastructure; ad hoc; QoS; routing; topology; control channel

I. Introduction

The spectrum is a limited resource. Military tactical networks are expected to support a greater number of services, and the bandwidth requirements of many of the new services are also rapidly increasing. This means that we are gradually getting closer to a situation where there will be insufficient bandwidth to support future military operations. Additionally, in the battlefield the spectrum availability can vary quite drastically depending on the geographical location and with transitory and long-term communications patterns. Furthermore, many future military operations will likely be undertaken by several participating nations cooperating in a coalition force. With the increasing demand for radio communication in such operations, it makes sense to dynamically coordinate and share spectrum between different participating nations.

Dynamic Spectrum Access (DSA) is a concept for non-static spectrum utilization. A promising approach for implementing DSA is Cognitive Radio (CR). A CR senses its environment and takes the decision to dynamically adapt its transmission parameters, e.g. the used frequency. That requires the capability to change frequencies without interrupting communication and without interfering with other radios. In [1], these functions are denominated spectrum sensing, spectrum decision, spectrum mobility, and spectrum sharing.

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CR has so far mostly been identified with exploiting unused frequency bands licensed for TV. The idea is that an unlicensed radio, called Secondary User (SU), can use a licensed frequency band when the license holder, the Primary User (PU) is not using the band. The idea was first promoted by Mitola [31] in 1999.

DSA can be realized both in infrastructure-based networks and in ad hoc networks. An infrastructure-based network is usually organized in a centralized way, featuring a main entity such as a base station or an access point. In contrast to that, ad hoc networks do not have any infrastructure backbone and are organized in a distributed manner. Both types of networks can be enhanced using CR technology to allow for real-time adjustment of spectrum utilization in response to changing environments and objectives. Nevertheless, there will be differences between the enhancements regarding multi-hop architecture, the dynamic network topology, and the time and location varying spectrum availability.

Networking in a radio is responsible for making sure that messages are transmitted on the optimal route with the highest possible quality. In a dynamically changing environment, such as a military operation, this can be a challenging task. Especially when using CR networks, the link quality might vary with every frequency change. Nevertheless, a CR network possesses advanced situation awareness, e.g. the knowledge about the spectrum environment at different places. This information can be used to optimize network properties, which requires that networking parameters are adapted based on spectrum conditions and exchanged between network nodes. Our paper will identify such parameters and analyse the challenges regarding their optimization by CR technology.

The next sections will be organized as follows. Section II will look at existing infrastructure-based CR networks and analyse their use for military purposes. In Section III the characteristics of ad hoc networks, like clustering or routing aspects, will be studied regarding their application to CR networks, with a focus on military networking. Design options for a common control channel in military CR networks will be presented in Section IV. Section V will conclude our findings.

II. Infrastructure-Based Networks

Infrastructure-based solutions are the field with most progress so far within Cognitive Radio, with the availability of IEEE 802.11af [32] and IEEE 802.22 [33]. There is also work within national regulation bodies and standardisation organizations within the field of databases for cognitive radios.

A. *Existing standards*

IEEE 802.11af and 802.22 are the two current standards for infrastructure-based CR. 802.11af allows WLANs to exist within frequency bands allocated to TV transmission. IEEE 802.22 is a long range (30 to 100 km) point-multipoint solution aimed for rural areas with limited broadband services available. For both IEEE 802.11af and 802.22, it is the base station that will coordinate the frequency used by all the clients (CPE – Customer Premise Equipment) connected to that base station.

Both standards cover usage of TV white space in frequencies from around 50 MHz to around 900 MHz, but will also allow operations in the 3 GHz band. Both standards coordinate frequency usage through some form of centralized database. How this database is implemented, and how CRs should use such databases will depend on the regulatory body in each nation.

Co-existence of IEEE 802.11af and 802.22 is covered by the standardization group within IEEE 802.19 [35]. IEEE 802.19.1 regulates co-existence within the TV white space.

1) *IEEE 802.11af*

The IEEE 802.11af is an extension that allows Wi-Fi to coexist as a secondary user in the TV white space. The standard only covers the radio interface part of the system. Communication with neither a centralized database, nor implementation of the database itself is part of the standard. Different bodies are standardizing the database; ETSI BRAN [37] in EU-countries while IETF PAWS [36] makes a generic standard.

The US Federal Communication Commission (FCC) and its counterparts in EU have different approaches and regulations for 802.11af. FCC allows for 48 hours between updates of the base station, with frequency bands of 6MHz and power emission at either 100 mW or 40 mW depending on proximity to any primary user. In EU, the "lease" time is 2 hours for 8 MHz bands, and power emission is dynamic based on proximity to both primary users and other secondary users. Any mobility mandates a new request to the central database.

The architecture for IEEE 802.11af allows for nested base stations. This allows a base station to be a customer to another base station and use that connection to negotiate with the central database. Maximum range for 802.11af is 5 km.

2) *IEEE 802.22*

IEEE 802.22 is made for rural areas where broadband connections are not typically available. Maximum distance between a base station and a customer is 30 km, but can be extended up to 100 km.

Due to the extended coverage compared to IEEE 802.11af, 802.22 have more functionality for spectrum sensing and coordination. Each base station will handle the frequency negotiation for all its connected CPEs (Customer Premise Equipment). All CPEs can participate in the spectrum sensing process, and different base stations can coordinate directly in case of overlapping coverage between the base stations. Each base station is mandated to update the central database once per 24 hours.

B. *Other work*

US DARPA issued its DARPA XG program around 2003. The aim for the XG-program was not to build a new radio, but to enable technologies for dynamic spectrum access. The work has defined several modules that can be used for cognitive radios, ranging from signalling policies affecting the CR-function, setting radio parameters to signalling between cooperating cognitive radios. Successful testing has been conducted by modifying existing radios in use by the US DoD.

Within the EU research program, the project CORASMA [6] has explored cognitive radio systems.

There exists a proposal [38] for peer-to-peer technology for coordination between cognitive radio systems. One practical use-case used of the technology is coordination between Wi-Fi access points in a building or a campus. Proposals like this are identified to also cover use-cases where radio networks can coordinate their dynamic spectrum access through a common backbone, to which each radio network has a gateway.

C. *Centralized databases*

Both the standards mentioned earlier require central database for coordinating with both primary and secondary users. There will likely be a lot of different approaches within this field due to different regulatory restrictions in different nations. In US, the databases themselves are implemented by commercial vendors, under oversight of FCC. In other countries, like in EU, it is expected that government agencies will run these databases.

All the proposed solutions support a nested or hierarchical approach to implementing the databases. Each database might support a geographical area, a license band or following organizational structures.

A very important part of the database implementation is the message sets defined for communication between a cognitive radio and the database, or for coordination between databases. There are several efforts for standardizing these messages, with IETF PAWS and ETSI BRAN as two major efforts.

D. *Issues for military use*

None of the proposed standards support mobile users. ETSI BRAN do support and require a position update to the database each time a CPE moves more than 50 m. There is however a possibility to extend the proposed IETF PAWS recommendation since that protocol allows a geographical position to be described by a polygon. If that polygon is allowed to be a larger size, a cognitive radio can specify in which geographical area it wants to operate.

All solutions discussed earlier require exact geographical positions of the base station and the mobile users. This has both a practical side and a security side to it. Implementing GPS in all radio systems will lead to a high cost, but we already see that some radio systems include a GPS-receiver as standard. The security issue might be a larger problem. A centralized register of the location of all CR-enabled radio systems might get too high classification to be of practical usage. In addition, these positions might be in different security domains, thereby severely hindering the exchange of such information between different databases.

One possible use-case for infrastructure-based CR-technology is to coordinate different Combat Net Radio systems that are connected to a common backbone through a set of gateways. None of the standards supports this use-case. IEEE 802.11af might partly support this by allowing nested base stations. This use-case might need extensions of the protocols, but is likely to be useful for the military community.

The current proposed message sets for database communication are tuned to intended frequency bands of 50 to 900 MHz and 3 GHz. Military cognitive radios will most likely operate outside of these frequencies. These protocols need to be studied further to check if other frequency bands will be supported.

E. Ideas for use in military networks

The two proposed standards for infrastructure-based CR have in themselves dubious usage in military networks, but they might be highly valuable starting points for new technology that might enter military networks in the future.

Both the standards are for point-to-multipoint static networks. Today, there are few deployments of such networks in military systems. It is however likely that armed forces will start to use that kind of networks more frequently in the future. The advantages of LTE and similar technologies will lead to an increasing number of base station technologies. IEEE 802.22 could be an alternative for relatively static operations like some of the operations NATO has been involved in lately in nations like Afghanistan. Likewise, technologies like 802.11af might have its use-cases within deployable field Headquarters.

A more interesting aspect is what a common database and protocols for exchanging radio parameters can have for military networks. There are two approaches to this; 1) using the exchange protocols for better and faster spectrum management, and 2) utilizing the central database for network aspects.

Policy language and database approach might utilize much faster and simplified (in man hours) spectrum coordination and management in a military operation. Each nation, unit or similar in an operation can coordinate their frequency requirements and usage much more dynamically thanks to a formal language understandable by computers. This dynamic frequency management can even be performed with both legacy and cognitive radio systems.

Network layer access to the frequency databases might allow for a range of new exciting functionalities:

1) Seal-healing from electronic warfare

If an adversary performs electronic warfare by jamming our network, there are several ideas that can be explored. On the CR-level, frequencies might be "moved" between geographical areas so that the radios closest to the jammer are allocated frequencies outside the jamming range.

If the databases receive information about jamming through the spectrum sensing functions in the cognitive radios, the routing layer can take this into consideration and move traffic away from the affected areas.

2) Spectrum-aware routing

The routing protocol can be informed about the availability of spectrum in different parts of the networks. This might be used by the routing protocols to route majority of the traffic through parts of the network with good availability of frequencies. The routing protocols might also take link quality and similar parameters into account if those are available in the database.

3) Traffic-aware DSA

With cross-layer communication between the network layer and the spectrum databases, information from the network layer can influence the spectrum allocations. The network layer can inform the database about traffic volumes and possibly the location of the important or heavy users of network services. The database can then allocate more frequencies to the parts of the network with large amount of traffic.

III. AD HOC NETWORKS

Cognitive Radio Ad Hoc Networks (CRAHN) are characterised by distributed multi-hop architecture, dynamic network topology, and time and location varying spectrum availability. Compared to classical ad hoc networks, CRAHNs can operate in wide frequency range varying in time and space, while in a classical approach, whole networks operate mainly on one or more predefined channels all the time. The CRAHN's users can use the spectrum allocated to the PUs if it is not used, and they must vacate it in other cases to protect the PUs transmissions. In CRAHN, each node can detect different spectrum availability according to the PUs activity, which limits global network management and optimal resource allocation and utilisation. Additionally, classical ad hoc networks generally use periodic beacon transmission in predefined channels to ensure topology control.

Since CRAHNs can operate in wide range of channels depending on PU activity, controlling the network topology is very difficult. It leads to the problem of unstable network operation. A further CRAHN feature is a multi-hop end-to-end transmission using many different channels. It influences the routing algorithms that need to find and build the paths composed of the links with different characteristics, depending on allocated bandwidth in any part of the network. Moreover, the PUs activity allows frequent channels handoff, which influences the end-to-end transmission regarding routing and quality of service (QoS) support. It is also required to distinguish typical user mobility from bandwidth handoff. Both events influence routing algorithms in the CRAHN. User's mobility is taken into account in classical ad hoc networks routing protocols, but frequent bandwidth handoff may lead to the slow route recovery.

In order to adapt to the dynamic spectrum environment the CRs perform following functions [1]:

- spectrum sensing,
- spectrum decision,
- spectrum sharing,

- spectrum mobility.

Each function influences different layers of the CR and then the operation of the whole CRAHN. Spectrum sensing process operates mainly in PHY and MAC layers and it can provide the information about the spectrum availability to the other functional processes and upper layer protocols. Spectrum decision process is responsible for selecting appropriate channels based on the sensing results and spectrum sharing procedures. Spectrum decisions should also be made based on the user (applications) requirements resulting from the QoS assumptions. In order to allocate appropriate channels to the network, the CRs have to communicate using network layer. The spectrum decisions should also cooperate with the routing protocol to adjust the routes according to the routing metrics calculated based on the links characteristics. Spectrum sharing process is responsible for resource allocation to the CRs in order to avoid spectrum overlapping in the network and thereby lowering the possibility of interference and collisions. Most CRAHN solutions in this area are focused on the clustering algorithms implemented in data link layers of the CRs. Such solutions support controlled and hierarchical resource allocation (i.e. channels are allocated to the clusters organised dynamically or depending on military units structure). High dynamics in clustering processes implicates high dynamics in resource allocation, and then network management. Spectrum sensing activity allows detecting free bandwidth that can be used by CRs. It leads to the spectrum handoff in some part of the network and in consequence to appropriate reactions of the topology control mechanisms and routing, transport and application protocols. Based on this introduction we can distinguish the following main CRAHN issues that should be raised:

- cognitive clustering,
- cognitive routing,
- cognitive topology control,
- cognitive data transport,
- cognitive QoS management.

The next sections are focused on identification and description of challenges of the above networking issues, especially in terms of military requirements.

A. *Cognitive clustering techniques*

A lot of research has been conducted in the field of ad hoc network clustering. Generally, two types of ad hoc network topology structures have been proposed [18], flat topology structure and hierarchical clustering structure. The flat topology structure used in wireless network composed of many nodes results in unstable topology, thus it is inefficient for self-organizing networks. Therefore, hierarchal clustering structures are often proposed. It can also be assumed that CRs will be operated in networks composed of many nodes. Some of the CRAHN solutions [6][12] propose hierarchical structures using clustering techniques. It gives possibility not only to better utilize the resources but also to organize the network according to spectrum availability, node's membership to the groups of interests, strongest links, or addressing. Additionally, in CRAHNs the network can be dynamically organised in clusters to support spectrum allocation, interference minimization, faster cognitive control messages flow and better cooperation between the nodes (i.e. cooperative sensing).

In military CRAHNs, there exist no mature solutions for clustering that effectively support cognitive functions. Further studies of the existing solutions are required, to either update the existing solutions or propose new ones that meet military CRAHNs requirements.

One of the challenges is to propose the clustering methods supporting a cooperative spectrum sensing. Sensing performance degradation can be observed due to the fading and shadowing that happens in the reporting channel, which forwards the sensing observations to a common receiver. Cluster-based cooperative spectrum sensing method may be applied to improve the sensing performance. Organising the SU network as a set of clusters with some cluster heads allows reporting sensing results to the common receiver with a spatial diversity.

When clustering is applied in the CRAHNs, the network also needs to support clustering technology. Routing boundaries and topologies should adhere to the clustering of the radios.

B. *Cognitive Routing*

Classical wireless ad hoc networks use wide range of routing protocols which construct typical routing tables keeping only the next hop and metric information. Most of them are based on proactive Optimized Link State Routing (OLSR) [22] or reactive Ad-hoc On-demand Distance Vector (AODV) [23] protocols with some modifications to adjust them to a specific wireless environment. For example, to select links with the highest transmission quality instead of the shortest route, OLSR uses quality extension by calculating the ETX metric [24]. Some of the routing protocols use geographical positions to find and select the best routes [25]. Others are equipped with mechanisms borrowed from nature (e.g. ant routing [26]). All of them are not designed for CR networks.

CRAHN routing protocols should not only find routes with the shortest path (or the path composed of the strongest links), but must take into account allocated channels in the network, PUs activity and potential channels that can be used, user's QoS requirements and other relevant channel characteristics. Moreover CRAHN routing mechanisms should cooperate both with spectrum sensing and spectrum decision processes during channel allocation. For example, next hop nodes have to be selected not only according to possible shortest path to the destination, but also based on the information about possible channels (and their characteristics) that can be used in the link between the nodes. The CR nodes have to collect information not only about possible channels that can be used (i.e. released by PUs), but also statistics about PU activity, to predict channels occupation time. This information can support CR nodes to perform both the routing and channel allocation decisions, taking into account end-to-end path and bandwidth stability.

The next problem with CRAHN routing is that the fixed common control channel (CCC) used in traditional routing protocols is infeasible. To find an appropriate path over the network that can use multiple channels, all the possible links (with different channels used) should be checked. When sending the Route Request (RREQ) message by some kind of reactive protocol in the CCC, just one common channel characteristic is taken into account. But, by expanding the route tables to cover the full channel usage along the entire path from the current node to the destination, the choice of channels may be so chosen to minimize the number of channel switches along the path [27].

Some proposals exist that are tailored to specific types of cognitive radio networks (for example [8], [28], [29]). They often do not meet military requirements in the area of reliable path (or multiple paths) selection and effective reaction on information from cognitive entities (route reconfiguration because of dynamically changing spectrum access or spectrum assignment policy). Especially TDMA-based radios are not taken into account. The set of metrics should be proposed that are relevant from military CRAHN's point of view and which can be effectively measured and used.

The routing mechanisms for military CRAHNs should:

- cooperate with cognitive entities located at each layer,
- cooperate with cognitive clustering mechanisms,
- support fast reaction on dynamic spectrum allocation and access (spectrum awareness routing, joint path-channel optimization, reaction on spectrum handoff),
- support dynamic network topology control,
- support high network survivability (route maintenance and reparation),
- support QoS requirements,
- support node mobility,
- ensure reliable connection with infrastructure-based networks and other CRAHNs (via gateways),
- optimise broadcast and multicast traffic and minimize signalling overhead.

Let us consider for example the TDMA-based network shown in Figure 1, where a CRAHN composed of the CR secondary users (SUs) operates in the area of a primary user (PUs) network. The CRAHN, in addition to using channels for its sole usage, can also use some channels allocated to PU network (channel 1, 2, and 3). The CRAHN uses hierarchical network organization, so it dynamically creates the clusters (using cognitive clustering) and allocates free channels for each cluster. To perform communication between SU1 and SU5, the routing protocol has to find an appropriate path (i.e. composed of a, b, c, and d links). For example, a standard OLSR-based routing protocol will recognize network topology using its inbuilt neighbour discovery and topology control mechanisms. The routing mechanisms at the network layer start operating after clustering and channel allocation procedures finish their work. They can rely on channels that have already been allocated and they recognize the neighbours depending only on the links characteristics (allocated channel dependent). There are some drawbacks of such a solution. Firstly, allocated channels can be changed during network operation (due to the spectrum handoff resulting from PU activity). The standard proactive routing protocol will react in the same manner as during SU node (or even whole cluster) movement using inbuilt mechanisms that are typically slow. Additionally, typical reactions provide sizable routing signalling traffic. Secondly, the OLSR uses its own solutions for signalling and route optimizations that are based on the multipoint relays (MPRs) selection. MPRs are selected using the criterion based on the maximal two-hop neighbours, which cannot be a good criterion in CRAHNs. Such approach allows selecting the MPR nodes that can perform frequent channels handoff, which can lead to network instability. Thirdly, clustering algorithms located in data link layers employ their own neighbour discovery mechanisms. Typical routing protocols located at the network layer will then superpose the neighbour discovery signalling on the clustering neighbour discovery traffic. These problems are also challenges for effective routing protocols for CRAHNs.

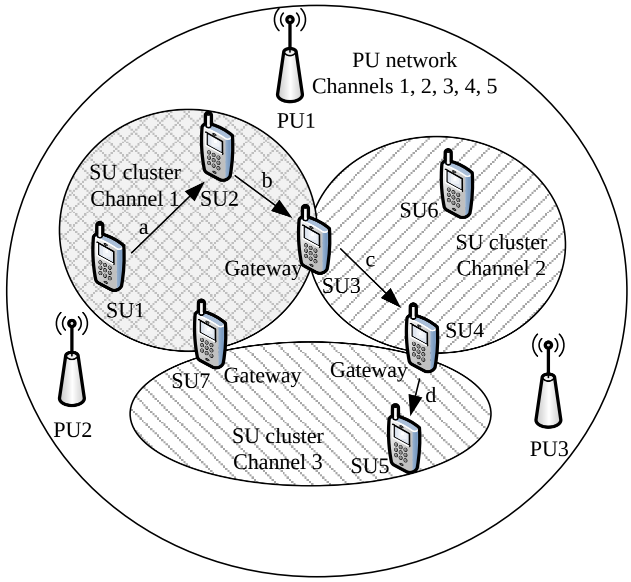

Figure 1. Network composed of PUs and CR SUs

Typical reactions on network or node mobility (caused by the spectrum handoff) can be changed over to solutions that cooperate with spectrum sensing and spectrum decision processes and also with cognitive clustering mechanisms in order to inform the routing protocol about the events connected with channel switching and cluster modifications. Also selection of MPRs can be adjusted based on the cluster organization. It seems to be reasonable that one of the MPR selection criterions should be the role of SU node in the network. For example, to minimize signalling overhead, the best MPRs could be cluster heads and gateways (nodes that operate in many channels – see Figure 1), but ones that are not overloaded and with predictable stable channels used in the cluster. Routing protocols can also use some work done by the clustering mechanisms and MAC to find the neighbours or to forward the frames (in some solutions, frames can be forwarded at data link layer without network routing). Finally, the actions can be inverted: before selecting the new channels (i.e. during spectrum handoff), current and predicted routes and route requirements should be taken into account. For sure, these proposals require cooperation of many cognitive entities such as sensing, spectrum decision and spectrum mobility processes, application requirements and MAC and clustering mechanisms. Moreover, the CR nodes have to keep and synchronize the database with all information coming from cooperation with cognitive entities in the given node and information received from other nodes. Collecting of such a comprehensive database is not an easy problem. Many effective mechanisms have to be enabled in the CRAHN to optimize the signalling overhead. The challenges presented above are not only valid for proactive routing protocols (i.e. OLSR-based). Nevertheless, such protocols are often used in military networks since they constantly build up the topology database, which can be easily extended and used for complicated metric calculation. Similarly, in CRAHNs it can be used to gather all information relevant for cognitive routing mechanisms.

C. *Cognitive topology control*

Network topology control consists of two processes: topology creation, and topology maintenance. Topology creation includes a process of neighbour discovery (ND). The CRAHNs that dynamically react on spectrum availability (and often spectrum handoff) are especially susceptible to effective ND. Most of the current ND mechanisms do not take into account radio node cognition features (i.e. sensing, spectrum management, sharing and mobility). The main challenge of cognitive topology mechanisms is to cooperate with cognitive spectrum access and routing algorithms. Topology maintenance (TM) processes should keep overall network connectivity and reliability during military cognitive network operation, taking also into account efficient reactions on military unit organization (i.e. group of interests), resource unavailability (i.e. because of jamming), network load, and QoS requirements.

As already mentioned, PU activity may enforce spectrum switching for many SUs, which is known as ripple effect. After this effect the network can be divided into new clusters, and a set of topology control mechanisms are initiated mainly on data link and network layers, resulting in packet dropping or significant packet delay for the affected users. The cognitive network topology must react on these events by controlling the effective traffic flow over the unstable part of the network (caused by spectrum handoff). One of the solutions can be a re-routing mechanism that re-routes packets along an unaffected path to avoid packet dropping and delay [21]. Other solutions [20] are based on maintaining a backup channel for SUs that can be used during spectrum handoff to send the packets, but these solutions are based mainly on predictable primary user activity that is difficult to achieve in a military environment. Some more solutions are proposed in [19], where Centralized Robust Topology Control Algorithm (CRTCA) and Distributed Robust Topology Control Algorithm (DRTCA) were elaborated. These algorithms are a mix of the algorithms proposed in [21] and [20] with some elements that do not need knowledge of PU activity in advance. Unfortunately, most of these proposals need beacons detections, which is not possible in military TDMA-based CRs.

The CRAHN topology control (TC), both at network creation phase and during network topology maintenance, needs ND mechanisms [9] [10] [12]. The effective ND solutions in military TDMA-based networks require cooperation between CR MAC, cognitive clustering, and cognitive routing. Typically, the routing protocols are equipped with topology control mechanisms (i.e. using Hello protocols and traffic control messages). In CRAHNs, an effective cognitive TC must be spread out between network and data link layer.

D. *Cognitive data transport*

The CRAHNs require efficient end-to-end data transport control algorithms. Standard TCP or UDP protocols are not designed for wireless networks. Some modifications proposed in literature can be used in typical ad hoc networks [16], but they are not efficient enough for CRAHNs. Transport layer protocols have limited knowledge of the network conditions in between the end nodes. Standard TCP is responsible for congestion control and data transmission rate adaptation of the source nodes to the receiving possibility of the destination nodes. It was designed for typical wide area fixed networks, where congestion comes mainly from intermediate nodes overloading. The modifications for wireless ad hoc networks provide the mechanisms that are able to identify a source of data segments loss: nodes overloading or wireless links characteristics (data segments loss because of signal fading and interferences or nodes mobility).

The CRAHNs provide new challenges in data transmission control. The data segments can also be lost or delayed because of spectrum mobility (handoff) and spectrum sensing. The TCP will react on such situation by decreasing the transmission window. Nodes could inform the source that it is a transitory state caused by the cognitive entities. Moreover, intermediate nodes that are particularly engaged in cognitive procedures can also work as something like proxy nodes for TCP transmissions. In CRAHNs, large bandwidth variations can appear in some segments of the networks according to PUs activity. Thus, the network can radically increase or decrease the throughput. TCP cannot adapt its transmission rate to such events in an effective way, especially in case of high data segment Round Trip Time (RTT). Thus, new bandwidth estimation methods have to be elaborated, that can use CRs characteristics. Some example proposals for bandwidth estimation can be found in [13] and [14].

The cognitive data transport solutions for military CRAHNs should propose updated or completely new connection management and congestion control mechanisms. They should take into account at least information on spectrum sensing, spectrum change, route failure and mobility prediction. One of the example transport protocol for CRAHNs is presented in [15] - the authors named it TCP CRAHN. It defines following stages: connection establishment, normal, spectrum sensing, spectrum change, mobility predicted, and route failure. Each of these states reflects the cognitive network behaviour and its influence on the node that has to control the data transmission. Similar assumptions are taken in TFRC-CR [17], where following states are proposed: normal, PU detected, PU exit, slow start, resume and paused. Both TCP

CRAHN and TFRC-CR can be taken into account during cognitive data transport mechanism elaboration, but there are still many challenges in CRAHNs that must be addressed. First of all, the solutions should be compatible with standard TCP and UDP protocols. The data transport connections can be initiated in fixed networks, where TCP or UDP is a standard protocol. Secondly, control messages should be reliably delivered (TFRC-CR and TCP CRAHN provide many control messages, but they can be discarded even if sensing or spectrum mobility is performed in some intermediate nodes).

E. Cognitive QoS management

Dynamic spectrum management gives a chance to increase a CRAHN network capacity, but also poses many problems in QoS management [11]. Users can utilize some new available spectrum won by a cognitive radio but appropriate information should be passed to the application to adjust traffic characteristics or user requirements. Once the available spectrum bands are characterized, the most appropriate spectrum band should be selected by considering the QoS requirements and the spectrum characteristics. Unfortunately, the spectrum characteristic can change dynamically because of both the network parameter modifications and PU activity. Thus, there is a need to perform both spectrum decisions and application interactions.

The cognitive QoS management also refers to the network management allowing appropriate network reconfiguration (i.e. routing, bandwidth reservation) in order to control traffic stream flows with different QoS requirements over different parts of the network. For example, in case some applications require so called hard QoS (i.e. VoIP), the packet flow should avoid network parts, which have allocated channels used by a PU network, especially if spectrum handoff is activated very often. And on the contrary, if some application streams are not delay sensitive, they can be sent over the nodes that won a new spectrum from PUs. Thus, the cognitive entities in CRs should deliver required information to the applications and should also exploit application requirements and specifications. The proposed cognitive QoS management solutions should take into account the military requirements on QoS.

Besides, in case of military networks, the ability to autonomously monitor, re-plan, and reconfigure the network requires knowledge and actions across different protocol layers. Network management mechanisms are therefore required. One solution for tactical networks is proposed in [30]. It is named Proactive and Adaptive Cross layer Reconfiguration (PACR) framework for network monitoring, analysis and reconfiguration in dynamic tactical networks. The following mechanisms were proposed: proactive network monitoring and prediction to achieve early knowledge of node/network problem, integrated cross-layer information sharing to reduce latency caused by layered architecture, advanced graphic model to assist fault diagnosis based on the real-time network topology and event information, and adaptive and dynamic network (re-)configuration. All these mechanisms influenced the QoS, improving the network mostly based on the COTS devices. Therefore, they should be further investigated.

IV. INFLUENCE ON THE CONTROL CHANNEL

The exchange of control information is one of the most important characteristics of modern communication systems. For example, ad hoc networks have to transmit hello messages for joining networks and to check whether an apparently silent node is still alive. Optimal routes in such a network are automatically determined and adapted via control messages. Cognitive radios use control messages to negotiate frequency changes. These examples show that such control information is used to set up, preserve and optimize data connections. Therefore, a reliable exchange is essential for communication systems.

Such control information is usually transmitted in a so called common control channel (CCC), which is a logical channel between all or a subset of the devices in a network. According to [2], a control channel can be classified as shown in Figure 2.

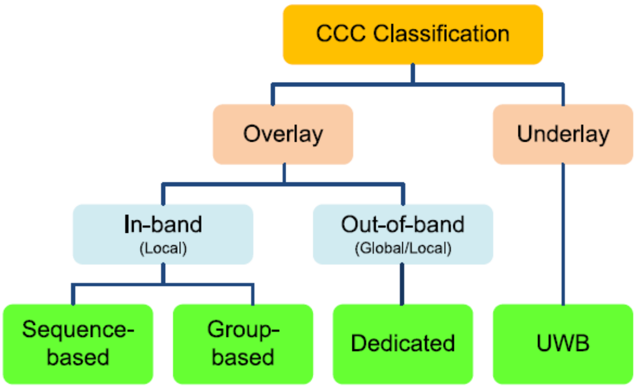

Figure 2. Common control channel classification [2]

Basically two approaches can be differentiated: a control signal can either be an overlay or an underlay signal, where the latter one is usually a UWB signal. In case it is an overlay signal, it can be either in-band or out-of-band, in relation to the data communication. While an out-of-band signal is always transmitted in a dedicated control channel, an in-band signal can either be designed in a sequence-based manner or in a group based manner. A sequence-based CCC allocates channels according to a hopping sequence, while a group-based CCC connects neighbouring devices with similar spectrum conditions. Sequence-based and group-based designs can also be applied to out-of-band approaches, as e.g. conducted in CORASMA [6].

In addition to that, in [2] four general design challenges for such control channels are reconsidered. The first one is control channel saturation. A CCC must be designed to transmit all requested control information in due time, therefore its capacity needs to be scaled sufficiently. A second challenge is robustness to primary user activity. In the same way as a cognitive radio must not hamper the primary user's communication, it must be guaranteed that an appearing primary user does not interrupt the communication of a cognitive radio network. The third challenge addresses the coverage of a CCC. As already mentioned above, one control channel may be used only for a subset of devices, e.g. in a clustered network. Nevertheless, it must be guaranteed that messages can be forwarded to all nodes in the network. Finally, security is the fourth challenge identified.

In the following, the challenges for overlay in-band, out-of-band, and underlay designs will be described, with a focus on military requirements. In addition to that, the influence of multi-hop connections will be addressed, and the impact on the OSI layers will be analysed. Finally, challenges for coexistence between networks will be investigated.

A. Out-of-band control channel

An out-of-band control channel means that control information is transmitted in a different spectrum band than the user data. A reason for this design is that a change of frequency exhibits the risk of losing connection; therefore it is comprehensible to only change the frequency of the user data channel and to have a constant control channel. Furthermore, there is usually much more user data traffic than control traffic, which implies that the control channel can have much less bandwidth. Thus, it may be possible to assign the control traffic to a fixed dedicated channel, even though there is not enough constant free bandwidth for the user data. That makes the network primary user on the control channel while being secondary user on the data channel. This either requires a second RF front-end, which is an unusual requirement for the used hardware, or fixed time slots for control information exchange, which presupposes a protocol supporting this and a front-end which allows fast retuning and fast bandwidth changes.

A dedicated out-of-band control channel, for which the network is primary user, requires a license. Another issue is how much bandwidth this control channel requires. Some examples of control messages, like hello or routing messages, have already been mentioned above. The negotiation regarding frequency changes requires exchanging the information about which spectrum bands are free. As this information may change very often and encompass a high amount of data, an exchange protocol needs to be developed that abstracts the spectrum information without loss of precision. In [3], a method called “hard combining” is proposed for this purpose. In this method the information about whether a channel is free or not is reduced to binary information, which can be transmitted in one bit, but that requires a unique numbering of the available channels.

From a military point of view, such fixed and licensed control channel exhibits vulnerability, as it can be easily attacked, which leads to a complete breakdown of the system. Therefore, an out-of-band control channel can be a single-point-of-failure (SPoF). It needs to be analysed whether a CCC can have transmission security (TRANSEC) features like low probability of intercept (LPI) and low probability of detection (LPD), e.g. by using UWB (see also Section 2.2.3). Furthermore, it is important to transmit as little control information as possible.

B. Exchange of control information inside the user data stream

Instead of having a separate frequency or even a separate RF front-end for transmitting control information, it is also possible to send control information inside the user data stream. This can either be done in a regular alternating manner or on request. The latter case means that control data is interlaced into the user data according to queueing theory. In order to minimize impact of PU activity, channel hopping can be applied (sequence-based CCC). In case a network is widespread, so that nodes at different ends of the network face different spectrum environment conditions, the network can be split into groups of nodes close to each other (and therefore observing similar spectrum availability). Such clustered networks have a group-based CCC.

As the control channel is not dedicated to a fixed frequency, the network cannot be a primary user on that frequency, but will always be secondary user. Nevertheless, as the used frequency is not known to devices outside the network, from a military point of view it becomes more difficult to jam the network. A further advantage is that the radio does not need to be retuned when changing between control and user data. But, as control and user data share the same logical channel, an increase of control information is also a decrease of data transmission capacity. In case the used channel is interfered, it might not be possible to negotiate a new channel or even to initiate the common change to an already negotiated new channel. A possible solution for this can be found in [4], where it is proposed to have a second receiver already tuned to a previously determined new frequency, so that the initiation of a frequency change can be conducted there. According to [5], it is recommended to use sequences with good correlation characteristics for such initiation messages, so they can be detected with high probability.

C. UWB control channel

UWB systems usually transmit their content spread over a large bandwidth. For short-range they have a very low energy level and allow for high data rates. The larger the bandwidth and the shorter the distance, the higher data rates can be achieved. In addition to this, UWB systems are able to share the spectrum with other systems. Information is transmitted by generating radio energy at specific time intervals, so that UWB signals consist of modulated pulses.

An UWB signal is per se less vulnerable to interference than non-spread signals, which makes it attractive for the use in control channels, but this reliability is only valid for small ranges. Nevertheless, most military communication requires medium or long-range user data transmission. However, if the density of a network is high enough, it can be possible to use UWB for multi-hop control information exchange (see also next section) while using medium or long-range waveforms for direct connections to other nodes of the network, which are not in direct vicinity. In order not to limit the distance of neighbouring nodes too much, a trade-off between range and control data rate must be found.

D. Multi-hop control information exchange

Not only for networks using UWB, but also for networks using other waveforms, it might be required that information is transmitted via multiple hops. E.g. if not all nodes of a network are in range of each other, it might be necessary to forward a message over several hops instead of using a direct connection. As a drawback, it must be regarded that each hop introduces latency to the transmission time of a message. Furthermore, in group-based networks some nodes do not even use the same transmission frequency. Therefore, gateway nodes are required to connect the groups. These gateway nodes temporarily use the frequency of one group and at all other time use the frequency of another group. A message passing such a node will have to wait until the gateway changes to the other frequency, which again is a source for latency.

From a military point of view the end-to-end transmission time can be critical in operations. Depending on the application, e.g. frequency change messages or sensor-to-shooter connections, there might be soft or hard real-time requirements. Therefore, the amount of hops and the delay introduced in each hop have an impact on the usability of the network for those applications. It needs to be analysed how to optimally configure the network dependent on the application.

E. Impact on other OSI layers

The impact on other OSI layers than the NET layer is mainly dependent on the selected CCC design. E.g. using underlay requires pulse modulation on the PHY layer. But there are also further requirements which are less obvious. When using separate front-ends for control and user data, co-site aspects need to be regarded. The prioritized handling of control messages compared to user data must be addressed when only one front-end is available. Furthermore, it must be analysed whether the control messages require unicast, multicast, or broadcast transmission.

In addition to this, the demands of other layers on the control channel need to be considered. E.g. the amount of sensing data exchanged for cooperative spectrum sensing can vary heavily. Therefore, the control channel needs to be sized accordingly. Especially in military networks priority is not only a technical matter for achieving QoS, but must also reflect the military hierarchies of the users, indicating an impact from the application layer.

In order to exploit the mutual influence of the OSI layers, efficient cross-layer techniques must be implemented. In [6], an architecture is presented, in which a cross-layer interface is introduced that allows for exchanging messages between all elements of the radio (layers, sensing, cognitive manager, etc.). That facilitates e.g. the NET layer to take influence on the PHY layer without sending a message through the MAC layer.

F. Coexistence between networks

In NATO operations, it often occurs that several nations use different waveforms in the vicinity of each other. Today interferences between those systems are avoided by giving each nation a set of frequencies for which they have an exclusive right to use, but still there are unconfirmed reports of interference between own forces. When CRAHNs will be fielded in the future, this exclusiveness will probably be abolished for the sake of spectrum sharing. Therefore, new ways of avoiding interference between systems from different nations need to be introduced.

A promising approach is that even though networks from different nations do not exchange user data, control information might be exchanged to ensure coexistence alongside each other [7]. This exchange requires some kind of CCC, and with this identical protocols as well as the capability to synchronise with each other become compulsory. Therefore, a common standard for such CCC is necessary. In the civilian world there are already task groups dealing with this topic (e.g. IEEE 802.19 and 1900.2). Their work includes existing waveform standards like IEEE 802.11, 802.15, 802.16h, and 802.22. As mentioned before, 802.11af and 802.22 are already aimed at using CR techniques.

Coexistence between networks implies that those networks automatically manage to share the available spectrum and to avoid interferences concerning both user and control data apart from the coexistence control information. Possible spectrum sharing solutions include using different frequencies, using TDMA on the same frequency, or achieving orthogonality on the PHY layer.

V. CONCLUSIONS

In this paper, we have identified challenges for network aspects of cognitive radio while taking into account specific requirements for military networks. We have considered architectural features of infrastructure and ad hoc networks, and we have analysed the influence on the control channel. Some issues of civilian infrastructure-based solutions have been identified and some ideas have been proposed for use in military networks. Several challenges have been identified for military ad hoc networks, namely cognitive routing, cognitive topology control, cognitive data transport, and cognitive clustering. A comparison between different control channel approaches has been given, namely out-of-band control channel and in-band control channel. Some of the challenges discussed in this paper have been addressed by rethinking the solutions developed for classical wireless networks and by taking into account some new information provided by spectrum sensing and spectrum mobility. However, more research is needed to ensure efficient spectrum-aware communication in military CRAHNs and to propose efficient protocols.

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