Tactical Applications of Heterogeneous Ad Hoc Networks – Cognitive Radios, Wireless Sensor Networks and COTS in Networked Mobile Operations

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Abstract— **Military tactical communications systems will be facing great challenges in the near future. Performance of commercial-off-the-shelf (COTS) technologies is improving at fast pace while at the same time life cycles of military equipment seem to remain long. The goal of this paper is to highlight a few interesting applications where development efforts of cognitive radio (CR), wireless sensor networks (WSNs), mobile ad hoc networks (MANETs) and commercial communications technologies would provide practical solutions from military point of view. The further work will focus on evaluation of CR as a part of heterogeneous military network. Importance of situational awareness on tactics and different technologies and their correspondence to tactical applications are discussed. Cognitive radio will find many applications in tactical networks but technical readiness is still lacking in some areas. A key issue in understanding the requirements of tactical networks is that the latest technology that is the most capable is not necessarily the most appropriate alternative. The focus should be on technologies whose effects on own actions and systems are understood thoroughly. This paper sets the groundwork for the research that aims at answering the question of what kind of military communications system should be built in the future if there are several requirements that limit the solution alternatives. The requirements to be considered are: 1) cost limitation, 2) limitation on number of units, 3) interoperability requirement, 4) mobility requirement and 5) performance requirement.**

Keywords—MANET; tactical networks; cognitive radio; wireless sensor networks; COTS; situational awareness

I. INTRODUCTION

Military tactical communications systems will be facing great challenges in the near future. Performance and capability of commercial civilian technologies are improving from generation to generation. Life cycles of military-grade equipment are typically much longer than life cycles of commercial technologies. On one hand, performance and high miniaturization level are tempting characteristics also in military applications. On the other hand, robustness of commercial technologies and security issues are not necessarily at the required level for military use. [1-3]

For the past few decades several ad hoc research projects have been carried out and quite many interesting results have been achieved [4-10]. Still, there are many obstacles for widespread use of mobile ad hoc networks (MANETs) [11-13]. Ad hoc networks have not been widely deployed due to better applicability and management of hierarchical and fixed infrastructure based networks. Ad hoc networks at their best are self-organizable and communication is based on short hops between nodes. Every node acts as a transceiver and a router that delivers internal and external traffic to other nodes at one-hop distance.

If we look very far to the future, it is likely that every node in the network actually is a cognitive MANET node due to technological advances and reduced unit costs. The goal of this paper is to highlight a few interesting areas where the development efforts of cognitive radio (CR), wireless sensor networks (WSNs), MANETs and commercial communications technologies would provide practical solutions from military point of view. There have been many research efforts concerning cognitive MANETs. Cognitive radio networks and WSN-assisted CR have been considered in [4], [21], [23], [25]. Many COTS-related considerations have not focused on cognitive radio but tactical radio issues. Dual use of VHF and UHF bands in tactical networks is considered in [24]. Military use of CR has gained more attention in recent years. Authors have not discovered similar approaches that consider the use of CR, WSNs, and COTS in MANET from the performance and cost point of view with the main goal of optimal solution.

The approach taken in this paper strives to understand the performance requirements, geographical coverage, mobility, connectivity, robustness and cost of the network. This paper sets the groundwork for a PhD research that aims at answering the question of what kind of military communications system should be built in the future if there are several requirements that limit the solution alternatives. The requirements to be considered are: 1) cost limitation, 2) limitation on number of units, 3) interoperability requirement, 4) mobility requirement and 5) performance requirement.

The following sections are organized as described here. First, importance of situational awareness on the battlefield and tactics are discussed in section 2. Section 3 looks to the future and describes some military applications that might use CR and MANET technologies. In section 4, different technologies and their correspondence to tactical applications

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are discussed. Section 5 concludes the paper and presents some research questions for further study.

II. Cognitive ad hoc radio networks and COTS in tactical applications

One of the most important factors in tactical operations is knowledge of operating environment and clever methods to benefit from awareness of surroundings. On modern battlefield, it is very important to preserve the communications channels between units in every situation. Due to limited resources and lack of development in radio research all units cannot be equipped with state-of-the-art radios. Therefore, awareness of operating area and understanding of radio propagation in different terrain and conditions is important. Own operation can be fitted to current situation if the location of units, terrain models, mobility of units and radio parameters are known.

In ideal circumstances, situational picture is received timely for the current and next phase of operation. Delivery of the situational picture could be handled as lightly as possible from the transmission point of view. Every node knows its own location and the nodes have a mechanism to report their own location to other nodes. Situational picture application shows the locations of own troops on the map and situation in the surrounding area based on the role of the user. The closer to the front line the user gets, the more time-critical situational information from the area is needed. Situational picture should be seen as a whole without every detail at the strategic level but there should be alarms of abrupt changes that might change the strategic situation, e.g., related to the capability of certain battalion at certain location. The level of detail depends on the operative status of the person, i.e., he/she receives the most urgent information for the current situation. The required information depends on location, order of battle and the next planned mission among other things.

Situational picture is formed by using as many sensors as possible. In the future, inexpensive nodes could run a situational awareness application as a background task without any effect on the user of the node. Since the continuous operation consumes a lot of energy in battery-operated nodes there should be a system-level mechanism that selects certain nodes to participate in the fusion of situational picture and lets other nodes sleep. This mechanism could be implemented as a part of the topology control messages. Coarse situational picture could be formed by a small number of capable sensors, and cheap sensors could be activated to create situational picture more fine-grained in areas of interest.

One should not underestimate the role of usability that has been taken more seriously in the commercial products. Most soldiers are used to use high-end technology products in off-duty so if these same methods would be used in military equipment, a great deal of resources could be saved in somewhere else than training the user interface of military equipment. Military-grade equipment has traditionally been heavy, large and hardly mobile. Large antenna structures and limited frequency bands create a challenge for modern mobile warfare. Networking capability of military units is also limited. The goal is to have a network that connects different communications systems more tightly together and guarantees the information flow to different units. Interoperability with some legacy systems could be provided by cognitive radios but interoperability with all previous military radio systems is unrealistic.

Deployment of CR on the battlefield forms a great threat for blue tactical communications so it is vital to take these issues into consideration in own concept planning. Development of a communications system should not be solely based on technological points of view but combination of defense tactics, strategy and technology should be examined in a way that allows flow of information and operational procedures to be optimized. This could be achieved by doing a thorough requirement analysis in co-operation of joint strategy and technology perspectives. Self-organization and autonomy should be applied at lower levels of hierarchy. Future systems are expected to be semi-autonomous but they require man-in-the-loop to confirm decisions, e.g., in offensive actions.

There are contradictory challenges to implementation of future military communications systems; on one hand, there is a need to form clusters that cover large geographical area, on the other hand there is a need for systems that are highly mobile and have a great computing capability. Due to cost pressures, one has to balance between the number of units and the level of performance of each unit. It is probable that a cost-fitted system consists of a large number of low-cost units and lesser number of very capable units that process data from low-cost units and connect those to faster networks. These requirements could be fulfilled by wireless ad hoc networks that are based on CR or software defined radios (SDRs). The use of SDR/CR based nodes as capable units allows the flexible collection of data from different units that operate at different frequency bands.

III. Future tactical applications of cognitive radio and wireless sensor networks

There is an ongoing progress towards software-defined technologies both in commercial and military applications. Software-defined functionality brings increased computing power and flexibility on the field but there are also evident challenges. The short-term challenge is to have versatile radios interoperable with each other and with new ones. In long-term, the situation may not be any better due to high unit costs of new multifunctional SDR/CR units.

This section takes a view to the future by considering few tactical applications that might benefit from SDR/CR technology used in ad hoc fashion. The detailed descriptions are given in the following subsections.

A. *Geospectral awareness*

There are several simulation tools that estimate the coverage of radio transmissions of, e.g., cellular base stations. These software programs use geographic data that contains height of objects, terrain types and land cover classifications. In the future, SDR/CR nodes will have a very high processing capacity so it may be realistic to assume that radio propagation calculation based on the environment could be done on the

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field. Requirements regarding power consumption and real-time operation will remain challenging issues in the long-term.

In this concept, SDR/CR performs at specific intervals calculation of radio environment that is based on accurate geographical data, height information, classification of terrain and radio wave propagation models depending on the selected frequency band. It is important to note that there is no need to have capability to real-time calculations. Calculation could also be done in a PC that is part of the backbone network and thus only visualization of the results is done at each node. Still, there are advantages of running the calculation in the node to limit the calculation load to communications link.

As a result of calculation, SDR/CR forms a frequency-selective awareness of the radio environment. Decisions can then be done based on that awareness. If the terminal is about to send a message to another terminal at known GPS location, based on the calculation the terminal knows where to move to have the best connection to other terminal. If the movement is for some reason impossible, the terminal can activate more appropriate waveform (automatically or by user action) to maximize the quality for that link. If the expected direction of interference is known, it can be used as a boundary condition. Then the user can move to a direction that minimizes antenna gain to threat direction and/or that maximizes the quality of the friendly communications link. Calculation is done at the selected frequency, since it would be very time-consuming to simulate wide frequency bands. Decisions, e.g., on frequency change could be made based on the spectrum awareness. Results of calculation are shown on the screen clearly with instructions on navigation to the best location in terms of radio environment.

B. Sensor network gateway and high-capability sensor node

SDR/CR node could act as a gateway or master node in a deployed WSN. Ad hoc sensor network collects sensor data and routes it towards SDR/CR that has high computing capability. In this type of scenario, backbone network and ad hoc sensor network do not have to be interoperable since SDR/CR acts as a gateway and provides transparent access to sensor data. SDR/CR has two waveforms onboard: both sensor network waveform and waveform for communication with the backbone network. Typically wireless sensors have limited resources so SDR/CR could also have some high-level sensors that require more processing power and higher data rate, e.g. video surveillance system.

C. Distributed interference detection and mitigation

Distributed interference detection would be an interesting military application. Dozens of nodes are distributed on an area and they are networked in ad hoc fashion. Every node knows its location. Nodes are routing the communications traffic in ad hoc fashion. Distant high power interference source is activated and the nearest pair of nodes detects that the quality of the link is too low for transmission. Instead of increasing the transmit power, the message is routed via other route. Nodes are aware of each other’s location, since the location data is shared for every node in the ad hoc network. The message is routed via second shortest path to destination node. If it is also interfered, new routes are tried until the edge of the network is reached. Based on the signal level, ad hoc network can estimate the direction of interference source and focus the traffic to the least affected route.

IV. DISCUSSION

In previous section, a few interesting tactical applications were introduced where CRs, COTS devices, WSNs and ad hoc networks could provide improved performance by working in collaboration. Since the application requires the use of CR technology in every node, consideration of that application is not realistic in short- or mid-term perspective due to high unit costs of CR units.

A. Node identities in tactical MANETs

If the cost of the wireless military network is an issue, then other solutions than using CR technology in every node, should be found. In the typical military scenario, there are different network islands that should communicate seamlessly with each other. These islands may represent a variable-sized group of soldiers, WSNs or other surveillance networks. Some of the nodes are fixed; some of those are mobile moving at different speeds. A characteristic feature of this type of network is intermittently changing topology and traffic load at different times.

Interesting topic to be considered in the research is the use of MANET functionality in mobile terminals. These terminals could be regular smart phones equipped with MANET technology that has a capability to connect and relay between other smart phones [21]. It is quite clear that MANET functionality between smart phones shows really important communications method after fixed infrastructure is not available or is destroyed. Base stations should be equipped with CR technology.

B. Frequency issues and vulnerability of MANETs

Typically the nodes in ad hoc network use the same frequency band that may be divided into separate frequency channels. The use of a common frequency band is possible due to limited transmission range and collision-detection and collision-avoidance methods. Frequency resources will be very limited in the future. The use of common frequency band enables the use of wide frequency bands that enable greater data rates. An application of direct-sequence spread spectrum and/or frequency-hopping in MANET is an interesting topic. Frequency-hopping provides robustness for the network but implementation is complex [14], [15]. Transmissions of other nodes and mobility in the same area cause interference and delays. These factors together lower the available transmission data rate. Due to low transmission power and radio transmission range, low probability of intercept (LPI) and low probability of detection (LPD) properties of ad hoc networks are satisfactory. The nodes are vulnerable under jamming but nodes have a possibility to deliver messages via optional routes unless the whole network is blocked.

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C. COTS and cognitive radio in tactical applications

Commercial communication technologies are more and more appropriate for military applications. There are many differences between a commercial CR and military CR. Requirements for military CR are e.g. robustness, long-term upgrade support from manufacturers, fast scanning speeds, very high frequency resolution, size, weight, power, interoperability with other communications equipment and the last but not least, security. Solutions should also be found to the question of how to counter hostile CR activities. CR traditionally preserves the capacity of the licensed primary users and tries to avoid interference to primary users at any cost. In tactical applications the same type of behavior is shown for neutral civilian bands but for the enemy bands the situation is totally different. Military CR tries to capture every signal that is possible from the enemy communications or tries to block every frequency that enemy tries to use for communications [16-20].

Many researchers have published results of communications simulation in recent years. The goal of those simulations has typically been optimization of network topology, performance of routing or MAC protocols, analysis of performance degradation due to mobility, calculation of radio transmission coverage or research of effects of external or mutual interference on communications [22]. The further study will examine these characteristics but the main focus of the research will be on evaluation of tradeoffs between performance of the network and cost of the network. Defense forces in many countries are facing the challenges of limited defense budgets, increased capability requirements, upgrading the military equipment in use and increasing prices of new military equipment. These challenges raise an important question: what level of capability and performance can be achieved at certain level of funding? The best capability and performance cannot be achieved with limited resources.

A key issue in understanding the requirements of tactical networks is that the latest technology that is the most capable is not necessarily the most appropriate alternative to military applications. The focus should be on technologies whose effects on own actions and systems are understood thoroughly. If the lacking points are recognized and mitigated then the technology selection could be successful. It is essential to consider the special requirements that military environment poses on technology. New technology can be taken into use by applying old tactics. Other alternative is to develop both technology and tactics in parallel. The latter method will probably lead to a better solution in a tactical environment. Life cycle management is an important factor in defense technology procurement planning. The performance of new technological capability, related costs, improvement of technologies, interoperability and upgradability of technologies make in the end technology selection hit or miss.

V. CONCLUSIONS AND FURTHER RESEARCH

This paper delved into issues raised by CR, MANETs, WSNs and COTS technologies in tactical wireless networks. The goal of this paper was to highlight a few interesting areas where the development efforts of these technologies would provide practical solutions from military point of view. Recognized challenges should be mitigated when applying those methods to heterogeneous tactical networks. CR would provide better use of spectrum that is limited for military users. Commercial cellular networks, e.g. LTE and femto-cells seem promising and direct access between handsets might provide more capability to ad hoc connectivity on the battlefield. Frequency-hopping in tactical communications networks evidently provides more protection for handsets that operate at long ranges. LPI/LPD features are not so important for WSNs that operate over small range, e.g. tens of meters.

The main research question is how a military communications network should be implemented in the future in order to reach severe performance requirements in different conditions but cost-efficiently. Cost-effectiveness has become a top priority lately with global economy recession, shrinking defense budgets and ever-increasing prices of military technologies. The focus should be on technologies whose effects on own actions and systems are understood thoroughly. Importance of situational awareness on tactics and different technologies and their correspondence to tactical applications were discussed. CR will find many applications from tactical networks but technical readiness is still lacking in some areas.

This paper set the groundwork for a PhD research that focuses on the following topics. Further study aims at answering the question of what kind of military communications system should be built in the future if there are several requirements that limit the solution alternatives. The requirements to be considered are: 1) cost limitation, 2) limitation on number of units, 3) interoperability requirement, 4) mobility requirement and 5) performance requirement. In particular, the following issues need to be taken into account.

- How is the cost limitation defined? There should be dependence between cost limitation and performance.
- Limitation on number of units comes from the fact that certain level of performance can be guaranteed to some percentage of units. It is not feasible to use many radios for one soldier. The cumulative performance may be better if every unit is co-operating than the performance of more expensive system where only few units have a high performance.
- Performance should not be created by degrading interoperability of the systems but all systems should be interoperable.
- Mobility requirement calls for high performance systems that can change position intermittently and can be functional even when moving at fast speed.
- Performance requirement is provision of certain level of communications capability in every condition, e.g., robustness, interference tolerance, geographical coverage and appropriate transmission range.

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