Tactical Radio Operator's Combat Readiness as Context Information for Dynamic Spectrum Management Within Military Mobile Ad Hoc Network

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Abstract. The Authors present a new approach to a method of dynamic spectrum management within military mobile ad hoc network. They propose that data concerning tactical radio operator's combat readiness be used as context information for spectrum management. The readiness is determined based on monitored vital signs of and interaction with the tactical radio operator. If the operator's inability to operate and protect the tactical radio is identified, actions are taken with the aim to release spectrum resources used by the tactical radio or in order to switch the tactical radio to modes used by search and rescue team.

Keywords: Dynamic spectrum management · DSM · Mobile ad hoc network · MANET · Combat readiness · Context information

1 Introduction

Due to its self-organizing ability and no need of fixed infrastructure, mobile ad hoc networks (MANETs) are of vital importance in military uses. They feature decentralized architecture, meaning that each node can serve as both a terminal and an agent for data transmission. Dynamic conditions of combat operations require modern communication networks to be highly mobile and able to collaborate with other units even if such collaboration has not been expected. This requires quick responses to changes within the network topology for the purpose of maintaining communication among the nodes. Unfortunately, routing updates among the nodes, especially in case of proactive protocols which are recommended for networks operating in destructive environments, e.g. in military environment [1], mean extra burden concerning control traffic.

A dynamic development of radio communication systems which has been observed in recent years calls for introducing more and more effective methods of radio resources control, depending on changing operational conditions. This facilitates optimal use of available frequencies and makes the communication service available to the greatest possible number of users.

A. Kliks et al. (Eds.): CrownCom 2019, LNICST 291, pp. 100–111, 2019.
https://doi.org/10.1007/978-3-030-25748-4_8

During a military action it may often happen that the spectrum assigned at the planning stage of an operation might not be used effectively due to a tactical radio operator's loss of combat readiness. Operator's combat readiness means the ability to carry out certain assignments, such as i.e. tactical radio operation and protection. Assessment of tactical radio operator's combat readiness may be used as context information [2] in MANET spectrum management mechanisms.

The structure of this paper is as follows: first, the authors present current state of affairs concerning dynamic access to spectrum within MANET, which is followed by a description of algorithms used for assessing tactical radio operator's combat readiness; further, the authors discuss the outcomes of applying the proposed solution, which confirm potential capability of its being used for spectrum management in networks featuring opportunistic access to the spectrum.

2 Current Methods of Spectrum Management

More efficient use of the available frequency band is possible thanks to applying a new philosophy of dynamic spectrum management (DSM). Dynamic spectrum management in MANETs may be effected through [3]:

- centralized management which uses a frequency broker featuring implemented spectrum tracking procedures, channel pre-definition and cognitive use of the channels by those network nodes which do not have any features of a cognitive radio,
- opportunistic management, dispersed management within MANET based on cognitive nodes (MANET-CR).

In case of centralized management, tactical radio operation is based on DSM application of coordinated methods of spectrum management in which it is equipped. Coordinated DSM is distributed within essential frequency bands dedicated to DSM, known as dynamic coordinated spectrum access (CSA). Coordinated DSM model uses devices supporting spectrum coordination within a given geographical region in order for them to decide about spectrum access within CSA. Spectrum coordinator collects information acquired from sensors directly from a tactical radio with DSM or from other nodes which sense the environment. The data is processed for the purpose of characterizing radio environment. Thanks to this, coordinators are able to assign free spectrum resources in response to access requests received. This ensures the system operability without causing harmful interference within and outside the network. Requests for assigning transmission resources are sent by tactical radios with DSM to spectrum coordinators by means of a dedicated channel. Spectrum coordinator assigns particular network users with a certain time limit, which is then used for the period of a communication session. Following the session, the channels are released and may be assigned to another system. CSA supports heterogeneous users whose requirements as to a band and operational parameters may cause mutual interference in the remaining users. Coordinated approach is more efficient in spectrum management than any hitherto used method, because thanks to CSA, a licence for a band is granted to each user, as opposed to assigning large portions of static frequency spectrum for use by particular services on a vast geographic area. Moreover, CSAs are assigned to a spectrum coordinator by means of automated processes rather than manual assignment of frequencies as it is in case of classical spectrum management. Such access management results in more flexible session-upon-session operation when the resources are needed.

Opportunistic management involves adaptation of a frequency distribution model, in which sensing of propagation environment is conducted autonomously by a number of tactical radios with DSM, and access to the spectrum is effected based on predefined spectrum management policies (SMPs), for own needs. Tactical radios with DSM, which make use of opportunistic access, identify unused portions of frequency bands in which they can operate without interference with primary users communication or without violating SMP. Tactical radios with DSM which operate within the area can mutually exchange information about the environment and coordinate mutual transmissions without spectrum coordinator support. Autonomous spectrum access (ASA) makes use of a set of frequency ranges which may include a combination of licenced frequency bands, CSA and non-licenced frequency ranges. Thanks to SMPs implemented in ASA, tactical radios with DSM opportunistic model are provided access to the available spectrum when other users are idle. ASA overlaps portions of frequency ranges which are defined by access or band sharing policies. Tactical radios which make use of opportunistic approach to DSM may operate within ASA as long as they observe the band sharing criteria. DSM presents a whole range of technical problems with implementing the method. The first one is a broad range of the spectrum, which may require sensing and describing its parameters. This would require tactical radios to be adjusted to detect broad frequency ranges and to be capable of transmitting and receiving throughout the entire bands. Current broadband antennas and radio technologies are still unfit for implementing that type of DSM in small radios, which could operate within broad frequency ranges. Secondly, DSM-type radios must be able to precisely detect the presence of other users within the band. If a certain band is deemed accessible by a radio, the radio must be able to collaborate with other DSM-type radios within the area in order to fulfil the requirement of not jamming one another. This calls for a development of a set of policies to set out requirements for cooperation of multiple radios within a given area and band.

There are many procedures for DSM use. The most important are the following procedures: "Command and Control" (C&C), "Exclusive Use" (EU), and "Common Spectrum Sharing" (CSS).

In case of "Command and Control" procedure a regulator grants a long-term licence for spectrum use. Such an approach is inflexible and results in unsatisfactory use of the spectrum resources. A slightly more flexible spectrum management method is based on seasonal right to an exclusive use of a frequency band, e.g. one which is not used within a given area. However, in case of long-term exclusivity one cannot talk about dynamic access to the spectrum, thus, neither of the above-mentioned methods belongs to DSA paradigms. Dynamic exclusive use is a method involving the assignment of short-term rights to access a certain frequency band by one user or a cognitive radio network. Another group of spectrum management methods is spectrum sharing with primary and secondary users. This method is based on a detection of a possibility to use the spectrum by cognitive radio devices and on protection of primary users' transmissions against interference generated by secondary users. Spectrum sharing may be effected based on the detection of white spaces in primary user's spectrum and use thereof by the secondary user.

In classical solutions, the above-mentioned spectrum management methods do not take into account a situation in which an operator has lost his/her combat readiness (due to a shot, loss of consciousness or death). In such case we deal with a situation in which a frequency band has been assigned to a tactical radio which is not using it. This may result in failure to assign spectrum resources to new tactical radios within the network. Hence the concept of spectrum management based on information about the life functions of a tactical radio operator.

3 Assessment of Tactical Radio Operator's Combat Readiness

3.1 Data Acquisition

A loss of combat readiness which poses direct threat to a soldier's life or health is most frequently caused by a shot, hyperthermia, hypothermia, a shot accompanied by cardiac arrest and loss of consciousness. Those conditions may cause acute respiratory distress, acute disturbance of consciousness, circulatory disturbance and thermoregulatory disorders. Based on an analysis of chief life- or health threatening conditions of soldiers in combat, the following vital signs have been chosen, which enable assessing health and general condition of a tactical radio operator:

- respiratory rate,
- oxygen saturation (SpO2),
- body temperature,
- blood pressure,
- heart rate.

Assessment of tactical radio operator's vital signs is extremely difficult due to a character of his/her actions which feature a great deal of mobility and a high level of stress. Both these factors significantly impact the values of vital signs monitored. This is why, when assessing vital signs, it is necessary to take account of data concerning current mobility of a person monitored (data acquired from a body position sensor and from a GPS receiver).

Information originating from I/O device which enables interaction with the operator may be an additional source of information about the operator's combat readiness. This device enables the operator to communicate a threat and to verify the operator's identity.

Possible data sources for assessing radio operator's combat readiness have been presented in Fig. 1.

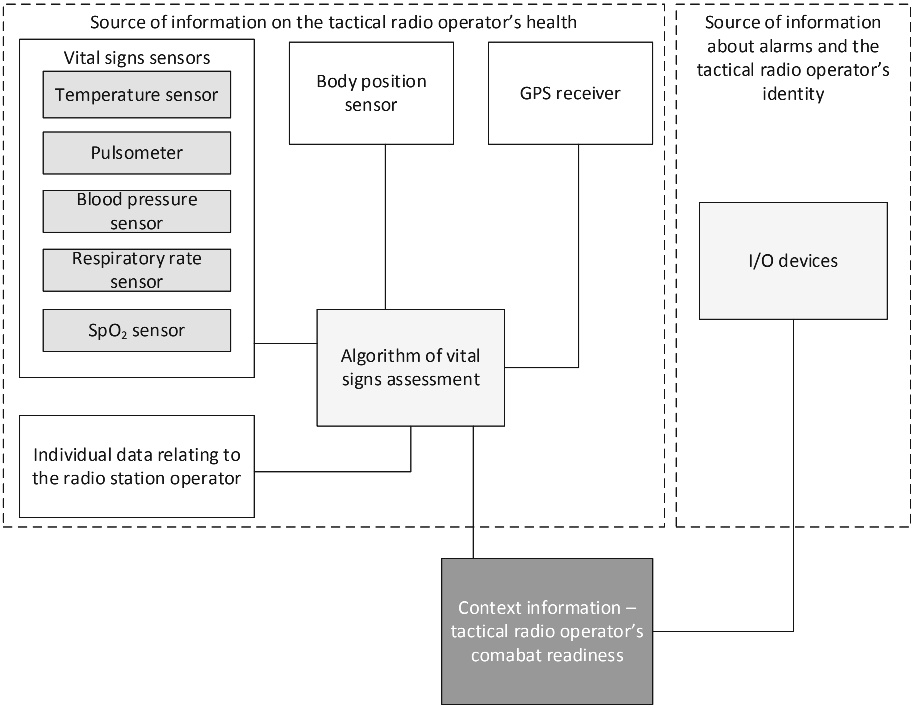

Fig. 1. Data sources for assessing tactical radio operator's combat readiness

3.2 Data Processing

As it has already been mentioned above, harvesting information about vital signs of a soldier in combat is difficult due to continuous mobility of the soldier. In addition, the signal received may be interfered with, which may cause inaccurate reading of the parameters. For vital signs to be assessed correctly, one has to apply an appropriate inference method, which will enable uncertainty modelling.

Inference Method

A method which makes it possible to effectively know true parameters from false ones and which is applied in case of insufficient information, is the Dempster-Shafer theory (DST) [4]. It is also referred to as the evidence theory or the theory of belief functions.

The DST is based on a set of all the elementary hypotheses, referred to as a frame of discernment Θ. In the DST model the frame is composed exclusively of non-overlapping elements, and its sub-sets are assigned a belief mass called a basic belief assignment (BBA), which is often marked as *m()*. BBA must have two properties:

$$m(\varnothing) = 0, \tag{1}$$

$$\sum\nolimits_{A \subseteq 2^{\Theta}} m(A) = 1, \tag{2}$$

where *m(A)* – value of basic belief assignment for hypothesis *A*.

According to the DST, hypotheses are assigned two functions: *Bel(A)* called belief function and *Pl(A)* called plausibility function. The belief function enables assessing reliability of clues for *A*, and the plausibility function assesses reliability of clues against *A*.

This theory makes uses of a relevant mathematical apparatus in a subjective assessment environment. It makes use of a level of belief and plausibility for the purposes of modelling the fuzzy assessments, and the assignment of belief levels to events and event groups is related with defining a distribution of beliefs.

The Use of the DST

The use of the DST makes it possible to define hypotheses thanks to which a soldier's condition can be assessed. Thanks to developing secondary hypotheses by means of a sum operator, it is possible to formulate imprecise and uncertain hypotheses.

Due to various types of vital signs subject to monitoring, initial assessment should be made separately for each of them. Records of data concerning various parameters may feature frequency of the data occurrence. Thanks to a separate assessment of those parameters there is a possibility to limit the number of secondary hypotheses without the need to use a hybrid model.

When assessing each of the parameters it is possible to formulate primary ("normal", "life-threatening", "serious") and secondary hypotheses ("uncertain serious", "uncertain life-threatening", "uncertain"). A hypothesis is assigned to particular measurements based on an assessment of the range of the value measured, individual features for each operator (age, sex, standard values of particular vital signs) and information on his/her activity. Thanks to a possibility to determine many hypotheses, this algorithm makes it possible, apart from defining the value ranges of a serious condition, to assume predefined critical parameter value ranges as a life-threatening condition. Table 1 presents extreme and alarming value ranges of particular vital signs, which are taken account of when assigning hypotheses to particular measurements.

Basic belief assignment value *m()* as determined in the DST is set for each hypothesis. It depends on a number of measurements to which a given hypothesis is assigned as well as on the time of observing them. Information concerning the measurement is accepted together with weights which depend on the time of observing a given event, thanks to which a change in a soldier's health condition can be detected more quickly.

$$m(x_1) = \frac{\sum_k w_k n_{1k}}{\sum_k w_k \sum_i^{|2^\Theta|} n_{ik}} \tag{3}$$

where:

$m(x_1)$ – basic belief assignment value based on measurements for hypothesis x_1;
2^Θ = $\{x_1, x_2, \ldots, x_N\}$ – a set of all the hypotheses, where $|2^\Theta| = N$;
n_{ik} – number of measurements assessed as x_i in k-ith time range of observation;
w_k – weight of measurement for k-ith time range of observation

Table 1. Alarming and critical value ranges of vital signs assessment.

		Individual person information – standard values of particular vital signs	Individual person information – age, sex	Lack of individual person information
Pulse	Life-threatening condition	Dependent on individual values	For men: 40÷50/min 120÷(205.8 – (0.685*age))/min For women: 40÷55/min 120÷(205.8 – (0.685*age))/min	40÷50/min 120÷140/min
	Serious condition	<40/min >(205.8 – (0.685*age))/min		<40/min >140/min
Body temperature	Life-threatening condition	Dependent on individual values	35÷36 °C 38÷39.1 °C	
	Serious condition	<35.0 °C >39.1 °C		
SpO_2	Life-threatening condition	91÷95% or > 99%		
	Serious condition	<91%		
Arterial pressure	Life-threatening condition	MAP < 75 mmHg SP dependent on individual values	MAP: 60÷75 mmHg SP: 60÷91 mmHg or 219÷249 mmHg	
	Serious condition	MAP < 60 mmHg SP < 75 mmHg or SP > 249 mmHg		
Respiratory rate	Life-threatening condition	Dependent on individual values	9÷12/min 20÷25/min	
	Serious condition	<9/min >25/min		

MAP – mean arterial pressure, the approximate value of which is determined according to [5] as: $MAP = DP + \frac{1}{3}(SP - DP)$, where: DP – diastolic pressure, SP – systolic pressure.

A final assessment of the soldier's condition requires taking account of correlated information on the vital signs monitored. Assessments relating to different vital signs are combined by means of a combination rule. Dempster's rule is a commonly used combination rule. However, it has got multiple shortcomings if the data is conflicted and values of some hypotheses near 0. Those shortcomings have been described in [6] and [7]. The literature abounds in interesting rules of assessment combination, which do not have limitations resulting from Dempster's rule, such as e.g.: disjunctive rule of combination [8, 9], Murphy's rule [10], Smets's rule [11], Yager's rule [12–14], Dubois and Prade's rule [15], Ali, Dutta & Boruah's rule [16].

Based on the analysis of the above-mentioned methods, due to the greatest concentration of basic belief assignment values when combining assessments for basic hypotheses, the Ali, Dutta & Boruah's rule was selected, which is defined by the following correlation:

$$m'(A) = m_1(A) + m_2(A) - m_1(A)m_2(A) \tag{4}$$

$$m(A) = \frac{m'(A)}{\sum_n m'(A)} \tag{5}$$

Based on the obtained values of basic belief assignment for all possible hypotheses, the condition of radio operator is classified as:

- serious,
- life-threatening,
- normal.

Node classification follows depending on verified hypothesis. Hypotheses are verified by means of a belief function defined as follows:

$$Bel(X) = \sum_{Y \subseteq X} m(Y), \text{for each } X \subseteq Y \tag{6}$$

where:

$X \subseteq \Theta$;

Bel: $2^{\Theta} \rightarrow [0, 1]$;
Θ – a set of all basic hypotheses;
2^{Θ} – a set of all proposals which were created from elements Θ by means of operator $\cup$.

Belief function's value is determined for basic hypotheses. Based on the determination of belief function values a decision is made to accept a given hypothesis.

Algorithm Verification
The accuracy of the operator's condition assessment according to the above-mentioned algorithm was verified for data generated on Hal S3201 adult patient simulator by Gaumard in relation to predicted changes of vital signs parameters under five scenarios:

- a shot,
- hyperthermia,
- a shot accompanied by cardiac arrest,
- hypothermia,
- a shot accompanied by hypothermia,

and for data originating from tests conducted by Centrum Ratownictwa Sp. z. o.o. on 16 healthy volunteers at rest and during activity. The data include values of previously determined vital signs (pulse, body temperature, respiratory rate, saturation, arterial pressure) with one-minute frequency.

The tests confirmed that the combat readiness loss under the five scenarios was detected correctly. In addition, the detection of the condition concerned under each scenario was done before the time the soldier should lose consciousness according to the doctors. In case of testing data originating from healthy volunteers at rest and during activity, in no case has the condition of combat readiness loss been misdefined.

4 Use of Combat Readiness Assessment as Context Information

There are many definitions of context information. A number of them refer to particular cases of use, such as e.g. definitions presented in [17–19]. A more general definition was presented in [20] by Dey and Abowd: *"Context is any information that can be used to characterize the situation of entities (i.e. whether a person, place or object) that are considered relevant to the interaction between a user and an application, including the user and the application themselves. Context is typically the location, identity and state of people, groups and computational and physical objects."* In order to define context, one has to collect adequate amount of information and to analyse it appropriately.

In our case, context information will include data necessary to assess combat readiness of a tactical radio operator. As it has been mentioned above, the information concerns vital signs and interaction with the operator. An appropriate analysis of the data will enable correct assessment of the operator's combat readiness and the detection of a condition which makes it impossible for the operator to handle and protect the ratio. This context may be used in a mechanism of dynamic spectrum management within MANET. If, during a military operation, loss of combat readiness is detected in a tactical radio operator, i.e. if it is detected that he/she has lost control of the tactical radio, it is possible to disconnect the tactical radio from the network, or to switch it to another mode of operation while releasing spectrum resources used by it. This is possible by remote control of the tactical radio by a commander who makes such a decision based on the data received concerning the operator's combat readiness.

5 Research

The goal of research was to verify a possibility of spectrum management within MANET based on information on tactical radio operator's combat readiness.

5.1 Research Environment

The research was conducted with the use of Harris's AN/PRC-117G tactical radios. They are multiband combat-net radios used currently in many regions worldwide, which enable operation within the frequency range from 30 MHz to 2000 MHz. The

AN/PRC-117G tactical radios are capable of operation in narrowband modes – 12,5 kHz or 25 kHz – and wideband modes – up to 5 MHz. Wideband mode is used by adaptive networking wideband (ANW2C) waveform. MANET is made up of tactical radios operating in ANW2C mode. This mode enables simultaneous transmission of data and voice within a radio channel. Both data and voice transmissions are protected by encryption (Type 1, NSA-certified). Data transmission within ANW2C network is based on IPv4 communication protocol. ANW2C mode uses time division multiple access (TDMA) as a medium access method. Maximum network size is limited to 30 nodes. ANW2C network may operate in two modes, namely with a fixed capacity allocation among all the users or in dynamic capacity allocation (DCA) mode.

5.2 Results

The presented method of assessing tactical radio operator's combat readiness may be used to control the work of radio network nodes. In case of AN/PRC-117G tactical radios one can use a set of commands recorded in ASCII format for this purpose. Radio operation may be controlled locally or remotely.

If a tactical radio operator loses combat readiness and radio control as a result of a military action, such a tactical radio may be excluded from the network or switched to another mode of operation, thereby releasing spectrum resources it has hitherto used.

Table 2 presents the results of research which illustrate an average data throughput for ANW2C network depending on a number of active network nodes. The research involved building an ANW2C network composed of 5 AN/PRC-117G tactical radios. One tactical radio was connected to a hypertext transfer protocol (HTTP) server, and the remaining four tactical radios operated as HTTP clients. The research was conducted account taken of two scenarios, i.e. with DCA mode enabled and disabled.

Table 2. 5 MHz ANW2C End-to-end user data throughput [kbps].

Number of active nodes	DCA disabled	DCA enabled
2	1120	2136
3	568	840
4	320	528
5	248	304

As we can see, in both cases an increase in the number of network nodes results in a division of available spectrum among a greater number of users, which translates into a decrease in average data throughput.

6 Summary

The article presents the use of information about tactical radio operator's combat readiness as context information which can be used in dynamic spectrum management mechanisms within MANET. The results obtained confirm a potential capability of the proposed solution to be used for spectrum management within networks which operate based on opportunistic spectrum access.

The solution presented may be used additionally to increase the security of military communications. Monitoring vital signs of a radio operator enables detecting combat readiness loss which results in inability to protect communications. This is particularly important when using Type 1 radios which enable transmitting NATO TOP SECRET information. If such a radio is no longer protected, it must be excluded from the network, including deletion of all the radio settings (encryption keys, mission plans). Moreover, constant monitoring of a radio operator's vital signs enables detecting a case of unauthorised takeover and adversary usage of previously authorised means of communication.

Acknowledgment. This article has been prepared under a project funded by the National Centre for Research and Development under a scientific research programme for state defence and security "Future Technologies for Defence – a Contest for Young Scientists".

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