# Dynamic Spectrum Management and Routing Solutions for Multi-Radio Mobile Ad Hoc Networks

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***Abstract*—The electromagnetic spectrum's scarcity, the tactical edge's dynamic nature, and the variety of tactical operations impose challenges to military cognitive radio networks. Multi-radio dynamic spectrum management (DSM) and routing promise to increase the spectral efficiency and robustness of tactical ad hoc networks by adding key control plane tools that adapt the network to the varying harsh tactical environments. This paper describes a novel concept where implicit spectrum sensing, a distributed DSM architecture with ontology-based spectrum access policies, modified routing and network time synchronization capabilities interplay to address those challenges. The simulation results verify the designed functionality in harsh electromagnetic environments in both small and large scenarios.**

## Introduction

Dynamic spectrum management (DSM) is supposed to provide improvements over today's fixed frequency allocation in highly dynamic and electromagnetically harsh environments. The scarcity of the electromagnetic spectrum provides further challenges to the frequency planning of military coalition operations. Cognitive radio networks are envisioned to provide high bandwidth to mobile users via heterogeneous wireless architectures through DSM [1], [2]. Due to the dynamic nature of the tactical edge and the diversity of tactical operations, the mobile ad hoc network (MANET) technology is considered fundamental for such networks [3], [4].

Tactical edge networks are composed of a variety of platforms (e.g. soldier, UAV, vehicular) and software-defined multi-band radios (e.g. HF, VHF, UHF, SATCOM). Although information can be relayed between these heterogeneous networks through gateways, the capacity of multi-radio terminals is not fully exploited before DSM and routing entities include the multi-radio interfaces into their algorithms. By also adding the concept of time synchronization across networks, these entities will enable a new level of spectrum efficiency.

The aim of this paper is to describe the studied tactical multi-waveform MANET characteristics and challenges, followed by a description of the selected architecture of DSM, synchronization, and routing, and how these interplay in order to achieve robust and fast dynamic reaction to sudden interference and jamming events. Finally, we show and discuss some simulation results obtained.

## Multi-radio MANET characteristics

In our study, the MANETs were restricted to operate in either VHF or UHF band, and each radio terminal could have 1–4 air interfaces in any combination of VHF and UHF. Figure 1 shows three MANETs (colored red, green, and blue) that are using either VHF or UHF waveforms, and the layering approach of the multi-radio network. The Lower NET is a routing protocol and forwarding functionality inside each MANET, and is thus an integral part of the waveform itself. The Upper NET is a routing protocol and forwarding functionality on top of that, dedicated to the internetworking, i.e., establishing forwarding tables that understand how the packets should be forwarded into another MANET. To support user A to user D communication, the Upper NET must provide forwarding tables in all such gateway radios, in this case, radio B and C. The more multi-radio terminals, the more flexible and reliable such interconnections will become. In a dynamic environment, with mobile users and electromagnetic interference, the challenge for the Upper NET is to keep the forwarding tables updated with an adequate compromise between control traffic load and update frequency.

The spectrum resources assigned to each frequency hopping MANET is assumed initially agreed and used as their initial hopsets, but there could be spare frequencies available to be assigned dynamically. Frequency reuse is applied when found appropriate, and where self-interference can be avoided. E.g., in Figure 1, the red and blue MANETs could be assigned with the same frequencies if the separation is sufficient to avoid interference. Thus, the DSM is in charge of the dynamic frequency coloring of MANETs. The DSM protocol should manage the spectrum resources in such a way that any interference due to mobility or external jammers is handled by algorithms that ensure the frequency hopsets are altered dynamically to avoid unreliable communication due to interference. A part of this solution is the enhanced Network Time Synchronization, that will ensure synchronization between MANETs to obtain

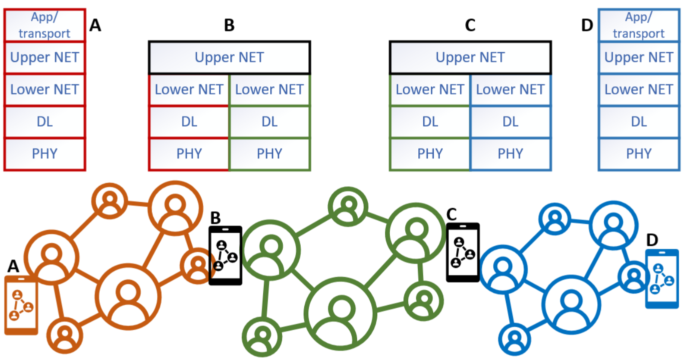


Figure 1. Radio A can reach radio D via B and C acting as gateways connecting three different MANETs.

a tighter frequency reuse. However, the main conductor is the DSM protocol, which is described in the next section.

## DSM SOLUTIONS FOR MULTI-RADIO MANETS

### ON SPECTRUM SCARCITY, COALITION COOPERATION, JAMMING AND INTERFERENCE RESILIENCE

Spectrum use can be intense in large military formations such as coalition deployments, with possibly hundreds of networks within interference reach of one another. When conventional spectrum management processes are applied, all the available VHF and UHF spectrum is often assigned to users and hence formally occupied. Still, all the spectrum is not really used all of the time. Typically, there are spectrum opportunities that can be exploited if the MANET radios can decide which spectrum to use at a given geographical location. Such local DSM is challenging in military networks, as it is also necessary to coordinate with non-communicative activities, such as electronic warfare. Therefore, compromises must be found between spectrum planning and coordination of spectrum use, and being able to swiftly adapt to the actual scenario of the operation.

Besides self-interference there could also be deliberate jamming. It is important that the VHF and UHF networks have resilience to both these sources of possibly degraded performance. Several design features have been added under the hypothesis that they would contribute to such jamming and interference resilience: (1) The use of combined VHF+UHF network radios with VHF+UHF routing may aid in routing packets around jammed areas; (2) Important control traffic, such as DSM signaling, is sent on both the VHF and UHF bands for redundancy; (3) A local DSM (L-DSM) in every radio reacts fast on sudden self-interference or jamming, by adapting frequency hopping patterns on network-by-network basis with the use of a set of available frequencies, previously provided by a central DSM (C-DSM); (4) The jamming and interference may break the connection to the C-DSM. If this happens, the solution should continue to work using only local information; (5) A wideband sensing entity should provide reliable information, concerning self-interference and/or external jamming.

### WIDEBAND SENSING

Our wideband sensing entity exploits silent periods in the physical layers of the VHF and UHF waveforms. With frequency hopping, narrowband sensing is performed at each hop and is gathered in a common wideband sensing representation of the VHF and UHF spectrum. Every radio in the network builds its own wideband representation of VHF and UHF spectrum after several hops. The solution can be used in military context without any significant effort from the signal processing point of view, as silent periods of synchronized VHF and UHF networks can be exploited based on the characteristics of VHF and UHF waveforms, i.e., the carrier-sense mechanism in carrier sense multiple access or the guard time mechanism in time division multiple access (TDMA). This approach allows a faster representation of the frequency

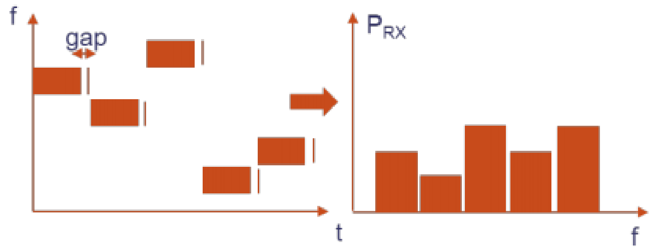


Figure 2. Representation of wideband sensing by exploiting silent periods in each hop.

spectrum for wideband sensing than a slot reservation approach and has no impact on the capacity of the VHF and UHF networks. An illustration of the solution is given in Figure 2.

The signal processing algorithms for wideband sensing are based on hypothesis testing. The different test statistics considered are the energy detection, the Anderson Darling, and the log-likelihood ratio based statistics associated with and without cooperative spectrum sensing [5], [6]. Depending on the test statistics used for hypothesis testing, only a small number of samples (20–80) is necessary.

### DSM DESIGN

The proposed DSM architecture has three DSM entities and one wideband sensing entity. The local DSM is divided into two parts: the “Fast L-DSM” and the “Intermediate L-DSM”. Figure 3 shows these entities as a green and a blue box, respectively. The C-DSM is shown in red, while the wideband sensing is shown in yellow. Their remote counterparts are shown in their respective colors, although in a darker variant. The architecture is motivated by the challenges that DSM systems face in military scenarios, with possibly intermittent or broken connections to C-DSM entities, and rapidly varying local spectrum availability. Dividing the DSM into three parts enables a loose coupling between the holistic spectrum management system and the local DSM, such that fast local responses to local changes in spectrum availability are possible even without online connectivity to C-DSM. The roles and interplay of the three DSM entities are outlined in the following.

*1) C-DSM:* holds the information about which parts of the spectrum are available at a given location and a given time. The information is in the form of an ontology (“computable conceptual model”) in the Web Ontology Language (OWL) [7]. The C-DSM also holds a snapshot spectrum use database,

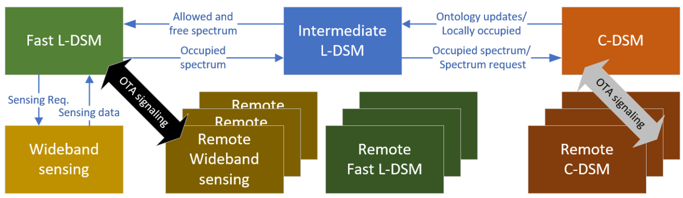


Figure 3. The DSM architecture with three DSM entities and the wideband sensing entity. Blue arrows indicate local entity communication in each radio, while thick black or grey arrows shows OTA communication.

keeping track of which networks currently use which physical frequencies and at which locations. At local spectrum changes, the Fast L-DSM informs the Intermediate L-DSM about the change and about the network's mean geographical position, and the Intermediate L-DSM relays this information to C-DSM. Selected "head" C-DSM radio terminals will broadcast such updates over-the-air (OTA) along with network ID and location.

*2) Intermediate L-DSM:* provides "free and available channels" in a given local area by reasoning on the latest copy of the ontology using the Semantic Web Rule Language Application Programming Interface (SWRL API) [8], and by performing requests to the C-DSM spectrum use database.

*3) Fast L-DSM:* is responsible for the actual spectrum that is used in a network. It gets available and free frequencies from the Intermediate L-DSM, as well as sensing data from the wideband sensing entity, and performs the spectrum change if needed. A spectrum change is a modification to the current hopset, such that one or more of the frequencies in the hopset are replaced. The Fast L-DSM assesses the possibility for current hopset modifications if at least one of these two situations occur:

i) Its local wideband sensing entity reports unusual high noise levels, or
ii) An incoming control message from a remote Fast L-DSM entity instructs it to act.

In case i), and only a single or a small portion of the used spectrum reports such noise levels, the radio will broadcast a message requesting any receiving radios within the MANET to respond with its noise levels on the indicated frequency. If any response is confirming a value above threshold, the Fast L-DSM will proceed to calculate a modified hopset, and to share this information using OTA broadcast signaling. This "Change current hopset frequencies" message includes old and new frequencies as well as the time of change. The time for change is selected with some latency, to allow all radios to receive the control message prior to this time instant.

In case i), and a large part of the used spectrum reports such noise levels, the radio terminal will conclude that Fast L-DSM operations must take place, without asking remote radios for confirmation. The rationale for this is to increase the probability of successful jamming mitigation when the spectrum is severely affected.

*4) DSM entities interplay:* When the Fast L-DSM has decided it needs to replace one or more frequencies in the hopset, it will get the frequency candidate list of "free and available channels" from the Intermediate L-DSM, by supplying to the Intermediate L-DSM the radius of the considered interference range as well as a Boolean "Siderule" parameter. When the "Siderule" parameter is true, only occupied channels to the west of own position are included when calculating free spectrum, whereas spectrum occupied by MANETs to the east is always considered free and can be used. In this manner, any spectrum conflicts may migrate eastwards, to possibly be resolved later at the edge of the theater.

Using the list of "free and available frequencies", the selection of a replace frequency is performed totally distributed by each radio, by seeding its pseudo random engine with the index of the affected interfered frequency. Since all radio terminals belonging to the same MANET will generate the same list of possible new frequencies, they will all select the same replace frequency. Only in the case of wideband jamming this condition may be broken, since the terminals might not detect all affected frequencies in the same detection event. To tackle such situations, a conflict resolution algorithm is included with a mitigation strategy to always accept the lowest replace frequency suggestion. This strategy also accepts to delete a frequency completely, in case the list of available replace frequencies has been emptied. The rationale in having a distributed replace frequency algorithm is to speed the reaction time, and being completely dynamic in constructing updated hopsets.

When a MANET is severely interfered, reliable control signaling can be compromised, and this makes it challenging to ensure that all radios that belong to this MANET will change to a modified hopset simultaneously. A way to alleviate this situation is to utilize overlapping geographical coverage of different MANETs. As an example, a long range VHF network can act as an "umbrella" network to broadcast the selected UHF control messages, or, vice versa.

## Network Time Synchronization

At the individual network level, network time synchronization (NTS) is essential for time synchronous communication schemes such as time division multiple access. It is also essential for maintaining orthogonal frequency hopping patterns among networks. This calls for inter-network NTS and could be called Extended NTS (ENTS). It increases overall robustness and can deliver the best available NTS timing source to different networks, e.g., a time from a global navigation satellite system (GNSS) if that is available. Details of the developed, generic ENTS algorithm can be found in [9]. Herein, the main principles are given.

ENTS is an entity that is active in multi-radio terminals. It takes NTS time information from the NTS algorithms in individual networks, decides which time will be used, and shares this information to all networks. Since this time is an external master time to the networks, the NTS algorithms must be capable of taking external master time source. Otherwise, the individual NTS algorithms are not touched. ENTS should be aware of NTS requirements in individual waveforms such that it does not force them to use a too loose time source. It applies policies set by end users. An example policy is that a GNSS time must be used if available, except if it does not violate the accuracy requirements, which may occur if the GNSS time is delivered from a distant narrowband system.

## Routing protocol solutions

The Upper NET enables dynamic routing between terminals in different MANETs. The routing solutions use a two-layer approach where the Upper NET layer is responsible for routing between the MANETs while the Lower NET layer is responsible for the MANET internal routing. The Upper NET sees all radios that are reachable by a MANET, via the MANETs internal routing, as one-hop neighbors. The routing daemon of the Upper NET is based on a modified version of OLSR, as described in [10].

The aim of the modifications is to reduce the amount of control traffic introduced by the Upper NET by utilizing (i) the Lower NETs capability of broadcasting packets to all radios reachable in a MANET and (ii) the topology information collected by the Lower NETs. The modifications are the following:

*1) Improved MPR (Multipoint Relay) forwarding rules:* Given the Lower NETs capability of broadcasting packets to all radios reachable in a MANET, the MPR in the Upper NET never retransmits a packet to the receiving interface.

*2) Compressed control messages:* A hybrid compression method is used that combines the vector approach from [10] with the (24-bit) prefix approach in [11], so that the best of the two methods is selected packet by packet.

*3) Link information from the Lower NET:* The detection of links at the Upper NET layer is based solely on information from the Lower NET layer. Links and associated neighbors are removed immediately when the corresponding link is detected as broken.

*4) Reactive Hello and TC messages:* When cross-layer information is available, there is no need to send Hello messages to discover links. Hence, a Hello interval of 512 seconds is used combined with reactive Hello messages that are sent on link and MPR updates. As in the OLSR standard, TC messages are sent in a reactive manner when changes in the MPR selection set occurs. The TC interval is increased to 60 seconds, at the expense of a possibly slower network merging. However, this is more or less avoided by using the TC message inspection method [10]. To further increase the robustness, additional control messages are sent after the initial reactively triggered message. It is done in accordance with [10], with a delay of two and five seconds for the first Hello and TC messages, respectively. To limit the amount of control messages, the interval between messages of the same type is at least two seconds.

*5) Link cost aware routing:* The algorithm is modified so that link costs can be associated to the links in the Upper NET. The cost is set to one for UHF and to 40 for VHF.

In addition to the described changes, it is assumed that the main address and interface addresses for each radio are assigned by a predefined address plan. Hence, the Multiple Interface Declaration (MID) messages are replaced by a parse of the address plan during terminal initialization.

## THE INTERPLAY OF DSM AND ROUTING

When a MANET, or a part of a MANET, experiences excess number of packet drops due to interference, the architecture with Upper NET and DSM has two measures to resolve the situation. E.g., assume that the green MANET in Figure 1 is severely affected by an external jammer, and that user A can no longer communicate with user D. If there exists a fourth MANET, located just south of the green MANET and that could be used as a bridge between the red and the blue MANET, the Upper NET should react to establish this rerouting. Simultaneously, the DSM entities have started to mitigate the infected part of the spectrum, and in the case there are enough free and available frequencies, a healed green MANET can be provided. While these redundant mitigation activities serve increased robustness, they can also pose some challenges due to increased OTA control traffic. Especially, for the narrow bandwidth VHF MANETs this issue was revealed problematic, and measures were implemented to be as traffic load conservative as possible without sacrificing functionality performance.

In the Fast L-DSM entity, a functionality named Quality Parameter Function (QPF) was defined that should serve spectrum and DSM information to the Upper NET. The following list of functionalities was assessed: (i) Interference levels and jamming situation in the two bands, (ii) Likelihood of receiving enough transmission resources, (iii) Link stability, (iv) Traffic congestion further away in the network, (v) Queue fill, and (vi) C-DSM information about planned forthcoming changes in the military theater. E.g., in (i), the Upper NET could utilize the message “severe interference in network Nx ongoing” to apply smarter routing protocol activities than without this information. The functionality Adaptive Link Selection (ALS) was defined in Upper NET to handle this kind of supplied information. Up to now, only option (i) has been implemented in the simulator, where the ALS saves a locked version of the routing table of the affected MANET air interface in the period when this interface is in jammed state. When the DSM has mitigated a jamming, or a jamming stops, the saved routing table will be reinserted, enabling a significant faster reschedule of packet forwarding through Upper NET.

## SIMULATION RESULTS

The work presented in this paper has been a part of a larger project with additional partners.[1] In this project, the MANETs are using VHF and UHF frequency hopping waveforms with a hopset size of 3–12 physical frequencies. The VHF waveform is based on 25 kHz STANAG NBWF, while the UHF waveform is a 1.25 MHz SC-FDMA waveform [12].The most prominent delivery of this project was the “MAENA simulator”. It is based on OMNEST simulator but with its own network scenario definition tool and performance metric database with dedicated visualization tools. The built simulator is not a conventional event based network simulator, since it also includes the PHY layer with channel coding and modulation I/Q sample waveform details. In addition, it includes synchronization capabilities, large and small-scale fading modeling, co-site interference, and path loss calculation using digital terrain maps. These features come at a cost of increase in CPU load and time of simulation experiments, but produce results with much improved credibility.

In the following, some results demonstrating the performance of the DSM and routing architecture in challenging network scenarios are shown.

[1]Besides the partners authoring this paper, Thales FR (coordinator) and Thales GE, Rohde & Schwarz, Fraunhofer, and Military Communication Institute (PL) have collaborated on waveform definitions and on the simulator.

### DSM/routing testing in smaller scenarios

The main purpose of such tests were to validate the DSM and routing capabilities with radios having up to four air interfaces, and that interfered frequencies in both VHF and UHF networks could be mitigated using signaling in both VHF and UHF networks. Additionally, the scenario should unmask the performance effect of DSM Siderule and ALS.

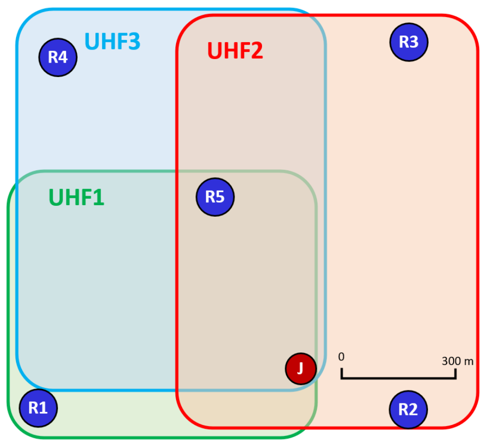


Figure 4. This scenario has 5 radios (blue) and one jammer (red). There are 3 UHF networks and one VHF network (for all radios).

The presented scenario in Figure 4 includes five radios (R1–R5), three UHF networks, and one VHF network. R5 is serving as a gateway between all UHF networks since it has 3 UHF (and 1 VHF) air interfaces. The other radios have one VHF and one UHF air interface. There are five UDP/IP flows lasting from 15 until 70 s: R1 to R2 via R5, R2 to R3, R3 to R4 via R5, R4 to R5, and R5 to R1, with a bit rate 40 kbit/s each. UHF2 is jammed at 20–40 s, UHF1 at 40–60 s, and UHF3 at 60–70 s. The VHF network is jammed at 30–40 and 50–60 s.

Figure 5 shows the packet loss ratio of all flows in four different cases. The black line shows the loss when the DSM mechanism is completely shut off, i.e., the conventional frequency management reference case. Between 20 and 40 seconds the UHF2 jammer strikes hard on the flows R1-R5-R2 and R2-R3. Due to longer range between the jammer and the affected radios in the 2nd and 3rd jamming events, the losses here are more restricted.

The blue line shows the loss ratio when DSM is activated with the Siderule and ALS functionality. The 1st DSM jamming mitigation is completed around 24 seconds, but due to independent operations between routing protocols of Lower NET and Upper NET it experience often a second phase of packet losses between 26–28 s. The latter is concluded as an artefact that could be addressed in a possible follow-up activity. Due to the Siderule only the eastern UHF2 DSM is taking into consideration other UHF MANET spectrum use, the activated replace frequencies of UHF1 (at 44.0 s) and UHF3 (at 64.0 s) might interfere with UHF2. This causes the residual packet loss events seen.

The red line shows the loss ratio when the Siderule functionality is off (but ALS on), which made all UHF networks to take consideration their neighbor networks spectrum use. As seen, after jamming mitigation further packet losses are totally

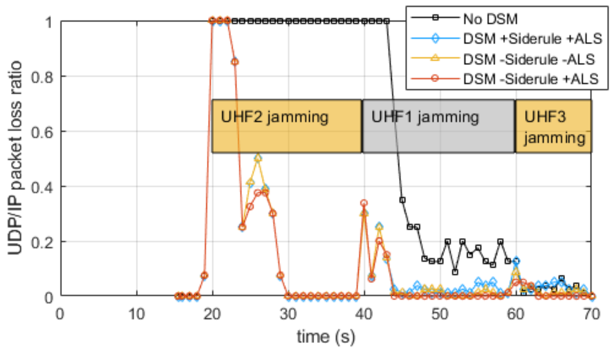


Figure 5. Sequential jamming – UDP/IP packet loss ratio maximums from all five flows, in four different DSM cases: No DSM, and DSM with and without Siderule and ALS.

absent. The results are inline with our design goals, since also the number of spare frequencies were sufficient in establishing orthogonality between the neighbor networks. The yellow line shows the results when ALS is off and reveals its benefits.

In another 5-radio scenario with all terminals belonging to the same UHF and VHF networks, a UHF wideband jamming attack (all 5 frequencies in the hopset) was mitigated after 3.5 s without any residual packet losses afterwards, indicating perfect DSM operation, even with DSM Siderule activated. In this scenario there were seven spare UHF frequencies, in which five of these were elected for the replacement hopset.

### Frequency jamming of companies and platoons in a larger military scenario

In order to validate the DSM and routing algorithms in larger operational scenarios, a multi-company scenario was implemented, consisting of 157 radios divided into 6 companies and 19 platoons. A UHF jammer attacks one frequency used in Company 4, and a VHF jammer attacks frequencies in its three affiliated platoons. The VHF and UHF jamming lasts from 35.0 s until simulation ends at 100.0 s. The UDP/IP traffic between the Company 4 radios (12 flows in total) all start at 40.0 s and end at 90.0 s. Such a large scenario takes a while to simulate. On a selected Intel i9 computer, each run took approximately 3.5 hours. In Table I, the overall UDP/IP loss statistics for the total of 45 flows (between all radios in the scenario) are shown, and results are obtained both with and without the DSM algorithm enabled. As seen, with DSM the packet loss statistics are reduced from 11.45 % to 1.02 % on average, which is very close to the result when jammers are

Table I
Large operational scenario – UDP loss rates (%)

| Simulation run | No DSM | DSM +Siderule +ALS |
|---|---|---|
| 1 | 13.65 | 0.85 |
| 2 | 12.38 | 1.30 |
| 3 | 11.46 | 1.19 |
| 4 | 9.29 | 0.01 |
| 5 | 10.24 | 1.13 |
| 6 | 11.65 | 1.61 |
| Average | 11.45 | 1.02 |

not activated. It can be concluded that the mitigation provided by DSM and routing works as anticipated.

## POSSIBLE FOLLOW-UP ACTIVITIES

The simulation results show that both the DSM and routing entities are working, and that their algorithms create significantly improved results (Figures 5 and Table I). The interfered frequencies can be replaced by non-interfered frequencies, and the Upper NET ensures that packet forwarding is resumed when the link is repaired by DSM or another route is found. We have, however, identified some issues underway, to be discussed next. The simulator itself will be an ideal platform to test and validate modified algorithms in follow-up activities.

Both L-DSM/C-DSM and Upper NET routing need OTA signaling. Due to the large capacity difference in the UHF and VHF waveforms, the VHF networks could easily be saturated by signaling traffic. Though the C-DSM OTA traffic was reduced during the development cycles, it can be further reduced by using the network position information more aggressively. The benefits of such reductions would be enhanced L-DSM and Upper NET routing performance, as well as VHF payload traffic throughput increase.

Some of the simulations indicate non-optimal collaboration between the DSM and the routing (see the prolonged packet loss period from 20–28 s in Figure 5). The simulation log reveals that the QPF-to-ALS mechanism reinserts the Upper NET routing tables correctly at 24 s, but the UHF Lower NET sends a cross-layer message shortly after that the link is not repaired yet, even with the new frequency hopset correctly activated. Around 28 s the Lower NET sends cross-layer message to Upper NET that routes are in place. The reasons behind this delayed protocol reaction needs investigation.

The built-in DSM “Siderule” capability has not been fully explored by the conducted simulations, when it comes to its capacity in pushing spectrum conflicts to the edge of the military theater. In comparing the results with and without the Siderule in Figure 5 in the period 40–70 s, it becomes evident that when Siderule is enabled, a network’s DSM replace frequencies might interfere with networks to the east, and occasional packet losses will occur. When the spectrum is crowded and interference is inevitable, the Siderule method has the potential of resolving conflicts even when parts of the spectrum is blocked by jammers. In future studies link packet losses signaled to the L-DSM can reveal the exposed frequencies for fast mitigation, and the C-DSM holistic spectrum knowledge can assist in long-term hopset changes.

## CONCLUSION

This paper has presented the main parts of a collaborative DSM and Upper NET architecture that is used on VHF and UHF networks. The utilized waveforms also benefit from network time synchronization functionality to assist the orthogonality between neighbor networks. It was shown that frequency jamming could be mitigated after just 3–5 seconds, and packet forwarding resumed shortly after. The architecture also showed good performance in large scaled networks, where packet losses were reduced from 11.5 % to 1.0 %.


## ACKNOWLEDGMENT

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## REFERENCES


[1] I. F. Akyildiz *et al.*, “A survey on spectrum management in cognitive radio networks,” *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 40–48, 2008.

[2] IST-140, “Cognitive Radio Networks: Efficient Solutions for Routing, Topology Control, Data Transport, and Network Management,” NATO STO, Tech. Rep., 2019.

[3] J. L. Burbank *et al.*, “Key challenges of military tactical networking and the elusive promise of MANET technology,” *IEEE Commun. Mag.*, vol. 44, no. 11, pp. 39–45, Nov. 2006.

[4] IST-124, “Heterogeneous Tactical Networks – Improving Connectivity and Network Efficiency,” NATO STO, Tech. Rep., 2019.

[5] M. A. Stephens, “EDF Statistics for Goodness of Fit and Some Comparisons,” *Journal of the American Statistic Association*, vol. 69, no. 347, pp. 730–737, September 1974.

[6] D. Teguig, B. Scheers, and V. Le Nir, “Data Fusion Schemes for Cooperative Spectrum Sensing in Cognitive Radio Networks,” in *2012 Military Communications and Information Systems Conference (MCC)*, 2012, pp. 1–7.

[7] “Web ontology language,” https://www.w3.org/2001/sw/wiki/OWL, 2013 (Accessed on 2022-01-25).

[8] “SWRLAPI,” https://github.com/protegeproject/swrlapi, 2021 (Accessed on 2022-01-25).

[9] H. Saarnisaari *et al.*, “Internetwork Time Synchronization of Mobile Ad Hoc Networks,” *IEEE Access*, vol. 9, pp. 84 191–84 203, 2021.

[10] S. Bergström *et al.*, “Routing Designs for Tactical Heterogeneous Cooperative Broadcast Networks,” in *2021 International Conference on Military Communication and Information Systems (ICMCIS)*, 2021.

[11] T. H. Clausen *et al.*, “The Optimized Link State Routing Protocol Version 2,” RFC 7181, Apr. 2014. [Online]. Available: https://rfc-editor.org/rfc/rfc7181.txt

[12] L. Rose *et al.*, “CORASMA Program on Cognitive Radio for Tactical Networks: High Fidelity Simulator and First Results on Dynamic Frequency Allocation,” in *MILCOM 2013 - 2013 IEEE Military Communications Conference*, 2013, pp. 360–368.


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