Robust group communications for mobile ad hoc networks

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Abstract

This is the final report of WP1 Robust group communications for mobile ad hoc networks, within NORDEFCO “Group-communication for military Mobile Ad Hoc Networks (MANET)”. The work is a joint effort by FOI and FFI.

In military networks a large part of the traffic is group communication, often called broadcast/multicast, that is, traffic aimed for multiple nodes. We study properties and improvements of two of the most interesting technologies for forwarding of group traffic to the interested receivers (multicast group). The study is performed for mobile military ad hoc networks, and the two technologies are Synchronized Cooperative Broadcasting (SCB) at layer 2 and Simplified Multicast Forwarding (SMF) at layer 3.

Keywords: SMF, SCB, ad hoc network, multicast routing

Sammanfattning

Detta är slutrapporten för WP1 Robust gruppkommunikation för mobila ad hoc-nätverk, inom NORDEFCO "Gruppkommunikation för militära mobil ad hoc-nätverk (MANET)". Arbetet har utförts gemensamt av FOI och FFI.
I militära nätverk är en stor del av trafiken gruppkommunikation, ofta kallad broadcast/multicast, det vill säga trafik riktad till flera noder. Vi studerar egenskaper och förbättringar av två av de mest intressanta teknikerna för vidarebefordran av grupptrafik till de adresserade mottagarna (multicast-gruppen). Studien utförs för mobila militära ad hoc-nätverk och de två teknikerna är synkroniserad kooperativ broadcast på lager 2 och ”Simplified Multicast Forwarding” (SMF) på lager 3.

Nyckelord: SMF, SKB, ad hoc-nät, multicast routing

Contents

1 Introduction

This is the final report of WP1 Robust group communications for mobile ad hoc networks, within NORDEFCO "Group-communication for military Mobile Ad Hoc Networks (MANET)"(**). The work is a joint effort by Swedish Defence Research Agency (FOI) and Norwegian Defence Research Establishment (FFI). Chapter 2 gives a summary of FOI's deliverables to WP1 whereas Chapter 3 gives a summary of FFI's deliverables to WP1.

In military networks, a large part of the traffic is meant for a group of receivers referred to as a multicast group. Hence, network functionality efficiently supporting group communication is required in military networks. Group communication has been addressed in many research programs up to now, both within the wired and wireless networks. However, military mobile wireless tactical networks tends to be more challenging due to mobility and time varying channels and therefore require additional robustness. In this activity, we have studied two different type of protocols/methods to provide the forwarding of group traffic to the interested receivers (multicast group) in a mobile military network. For group communication in mobile military networks *Simplified Multicast Forwarding* (SMF) [1] has been shown to be a robust technique that is suitable for many military scenarios. SMF can be configured for different levels of robustness at the cost of reduced resource efficiency. This is an OSI-layer-3 protocol that can be used on top of any underlying transmission technology.

Another interesting method is the more recently developed *Synchronized Cooperative Broadcasting* (SCB). The strength of SCB is the build-in robustness towards mobility. Furthermore, SCB is particularly efficient in case of broadcast traffic as all transmitted packets are received by all nodes in an SCB network. Therefore, for a single mobile network with high dynamics using SCB for broadcast traffic is preferred as it is both robust and efficient. SCB is an OSI-layer-2 protocol that must be incorporated in the transmission technology.

Both of these protocols aim to flood the whole network with the group traffic, thus there is no need to maintain multicast group state information, and both protocols use redundant packet transmission to improve robustness for mobility. They differ in the level of robustness they can achieve and in the flexibility for how the protocols can be deployed and used. In WP1 we have studied both of these techniques closer. For SCB several activities have contributed to a better understanding on how SCB can be used in tactical networks and the resulting performance. For SMF we have proposed ways to increase the efficiency and improve the flexibility of the protocol.

In Chapter 2, SCB is described and analyzed whereas Chapter 3 investigates how SMF can exploit elevated relay nodes and discuss SMF scooping. The conclusions from the research are presented in Chapter 4.

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2 Multicasting by Cooperative Communication in Mobile Ad Hoc Networks

Cooperative communications is a promising technique for addressing many challenges in ad hoc networks, such as robust communication under high mobility and transmission of time-critical traffic.

2.1 Synchronized Cooperative Broadcasting

In *synchronized cooperative broadcasting (SCB)*, all nodes that receive a packet retransmit it simultaneously. Packets that are relayed simultaneously from nodes within range are always identical, and a node receiving simultaneously transmitted packets from different relay nodes handle the received signals as multipath propagation. The retransmissions continues until all nodes in the local network have received the packet. In order to synchronize the relay transmissions, time is divided into repeated TDMA frames consisting of time slots. The SCB principle is used in for instance *Barrage Relay Networking (BRN)* [2].

To describe in which time slots nodes transmit or retransmit messages, we introduce the concept of a *Cooperative Broadcast Slot (CBS)*. A CBS is a subset of the time slots in the frame. The CBSs are of equal size and disjoint, i.e., the number of time slots in the CBSs is fixed and no time slot is a member of more than one CBS, see Figure 2.1.

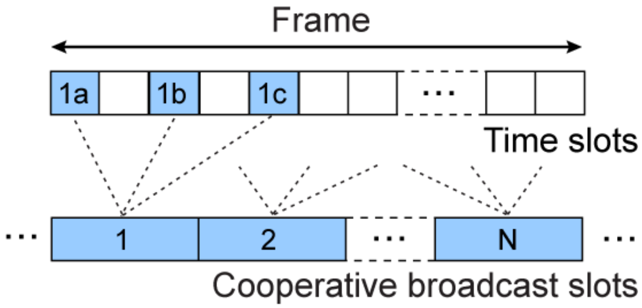

Figure 2.1. Cooperative broadcast slots of size three in a frame.

The time slots in a CBS are used for transmission and relaying of packets from a single source. Time slots are preferably selected consecutively from the time frame in order to minimize the relaying delay, but for radio systems with a large time difference between transmitting and receiving, the time slots have to be more separated. How the time slots are grouped into CBSs is predefined and does not change over time. The CBSs can be *scheduled*, i.e. associated with source nodes in the same manner as time slots are scheduled to nodes in traditional TDMA. The scheduling can be dynamic (to different source nodes over time) or pre-allocated statically. Each CBS can only be scheduled to one source node at a time. The source node is the only node allowed to transmit new packets in that CBS. All of the other nodes are restricted to relaying previously received packets in the CBS according to simple rules, described as follows. All nodes are synchronized and use time slots as a time reference when to transmit or receive packets. The frame repeats periodically in the sense that it starts over again with the first time slot after the end of the last one (see example in Figure 2.2).

All time slots in the CBS are *relay slots*, and one of those is also a *source slot.* The following rules defines for all nodes in the network what action to take in the relay slots from one (or several) CBS scheduled to a broadcast stream.

Forwarding rules in a CBS:

The source node: sends new packets only in the source slot and is silent otherwise.

All other nodes: stays in receiving mode until a packet is received. If a packet is received, and the node has not sent it before, the received packet is relayed in the next relay slot and the node returns to receiving mode again.

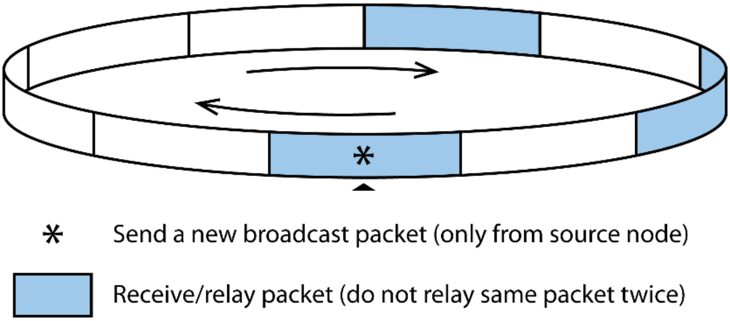

Figure 2.2. Broadcast forwarding example with one cooperative broadcast slot of size three in a repeating frame of nine time slots. A packet that is received in one relay slot is relayed in the succeeding relay slot in the CBS.

The size of a CBS is equal to the *reuse distance*, i.e., the minimum number of network hops between two nodes simultaneously transmitting different packets. We illustrate this property, and the broadcast flow in a network with an example in Figure 2.3 to Figure 2.6. A network broadcast of a packet is initiated by the source node, see Figure 2.3. The source transmit (indicated with blue color) a packet in the first relay slot (with label 1a in Figure 2.1). The large blue region indicate the nodes that receive, or already have received, the packet. In Figure 2.4, the nodes that received the packet in the previous relay slot (1a) relay it simultaneously in relay slot 1b.

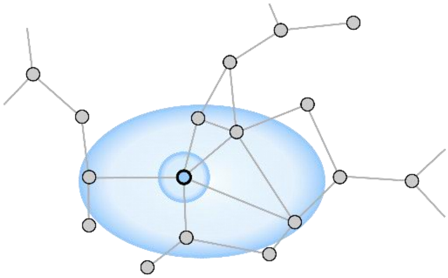

Figure 2.3 Illustration of synchronized cooperative broadcasting at the relay of slot 1a.

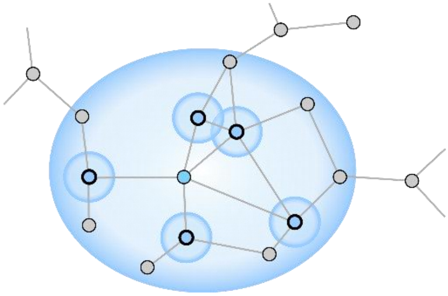

Figure 2.4 Illustration of synchronized cooperative broadcasting at the relay of slot 1b.

The relaying is repeated in Figure 2.5, in the sense that the nodes that received the packet in the last relay slot (1b) relay it further in the next relay slot (1c). The nodes marked with thick edges in the figure are the relaying nodes. All nodes marked blue in the figure have at some time got the blue packet. When all relay slots from the CBS has been used for relaying, the packet has reached a certain number of hops from the source (equal to the reuse distance). In the succeeding frame, the process starts over again from the source, see Figure 2.6, at the same time as the previous packet is relayed further. The source node transmit a new packet (yellow) in the initial relay slot from the CBS. Simultaneously, in the same relay slot, nodes further out in the network continue to relay the previous packet (blue) with a low risk of interference problems from other transmissions. A reuse distance of three as illustrated in this example is the theoretical minimum value, but in many cases a larger reuse distance is necessary to reduce the interference.

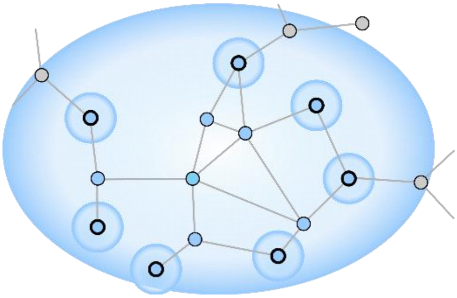

Figure 2.5 Illustration of synchronized cooperative broadcasting in the relay slot1c.

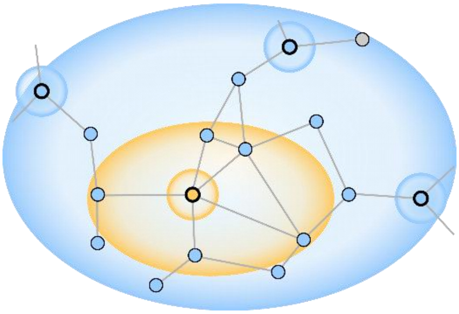

Figure 2.6 Illustration of synchronized cooperative broadcasting in the relay slot 1a in the succeeding frame.

2.2 Pros and Cons with SCB

Synchronized Cooperative Broadcasting (SCB) has both pros and cons when compared to classic ad hoc network techniques. Many protocols and algorithms have been developed for ad hoc networks, but common to the more advanced ones are that they try to adapt to the changing radio channel in different ways. For example, routing protocols are used to find paths through the network and to avoid various unnecessary re-transmissions. This applies both to point-to-point traffic and point-to-multipoint traffic. Changes in the radio network must be detected and topology information has to be updated. Redundancy can be used to reduce the problem, but this leads to reduced capacity. With SCB, topology information does not need to be updated, giving advantages as mentioned below.

- Robust toward mobility: No route updates are required, which significantly improves robustness. As long as there is a possible route through the network, packets will reach all destinations. The robustness is comparable to that of full flooding, but SCB is much more efficient in terms of delay and capacity.
- Low delays: The time slots that transmit the broadcast stream can easily be scheduled close to each other, which gives low delays, even over many hopes. In theory, this is also possible in a classic TDMA system, but any topology change requires updates of the transmission schedule, which takes time and is resource intensive.
- As no signaling traffic with topology information is required, the overhead in SCB networks is relatively low.

Possible disadvantages are

- Power consumption in the network can be relatively large due to all nodes retransmitting all packets, especially for handheld devices this can be a problem.
- Receiver complexity: A receiver capable of handling multipath propagation with relatively large delay differences is required. This may make the system more expensive, as well as affecting power consumption negatively.
- Unicast: SCB may be an ineffective technique for point-to-point traffic in terms of network capacity, even though it provides a robust transmission with low delays.

2.3 Performance Analysis of Reuse Distance Choices in Synchronized Cooperative Broadcasting

When transmitting large files, or in other cases when the network gets highly loaded, high network capacity is significant. The *Network broadcast capacity* is the maximum number of packets per time slot that can be broadcasted from the source to all destinations, where each packet perfectly fill a time slot. As nodes either can receive or transmit packets, the network broadcast capacity can never exceed one. A TDMA network with only one hop is an example of a network that can reach network broadcast capacity one.

In an SCB network we can broadcast one packet per CBS. As the reuse distance D is equal to the number of time slots in a CBS, the SCB network broadcast capacity is the inverse of the reuse distance, i.e., $1/D$. Therefore, it is essential that the reuse distance is kept as small as possible. However, if the reuse distance is too low, interference causes packet loss in intermediate nodes. Most studies of synchronized cooperative broadcasting are based on the protocol interference model [3] (a graph model). In this model the minimum reuse distance is three. However, using the more realistic physical-interference model [3] (signal-to-noise-and-interference ratios) the needed reuse distance is harder to predict analytically due to the time varying interactions between interfering transmitters.

In [4] we study how the reuse distance affects system performance in terms of robustness and network capacity. The study is based on network simulations using a realistic terrain-based channel model that allows the study of complex interference effects present in a real scenario. The focus of the study is smaller networks (up to 60 nodes), typical for mobile military networks, ranging from sparsely to fully connected, to see how the network connectivity affects the interference from time-slot reuse. In the following, we show some results from [4].

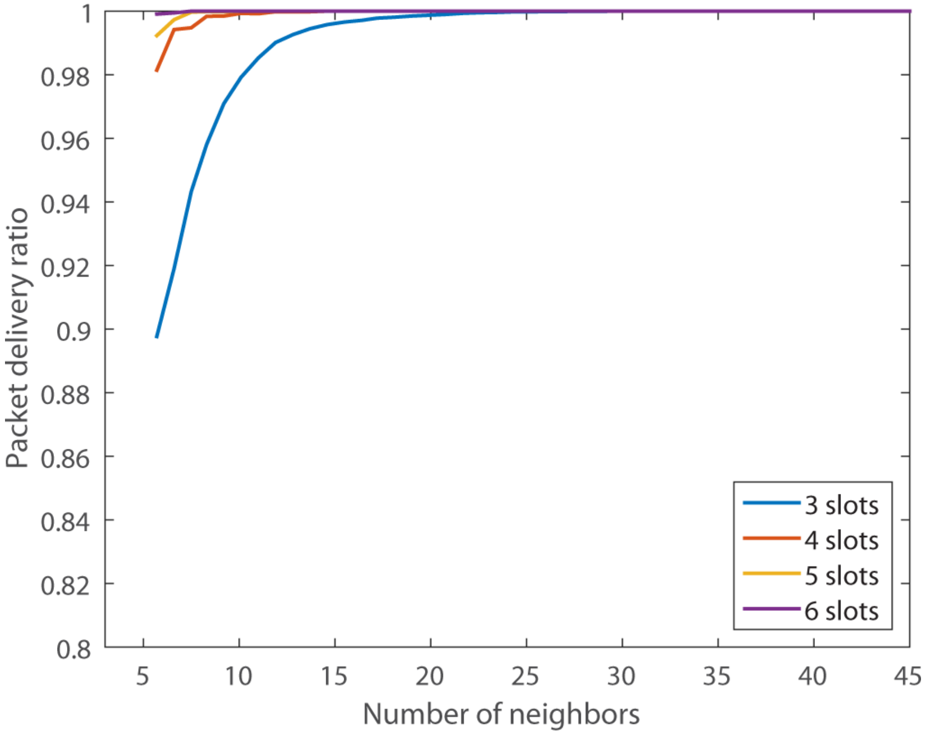

Figure 2.7 Comparison of different reuse distances.

The effects of different reuse distances (3, 4, 5 and 6) on the system robustness for 60-node networks using a spectral efficiency of 1 bit/s/Hz is shown in Figure

2.7. The y-axis shows the network averaged packet delivery ratio, whereas the x-axis shows the average number of neighbors. We see that a reuse distance of 3 is insufficient when networks become sparse, while a reuse distance of 4 is mostly sufficient. In [4] it is further shown that for higher spectral efficiencies even higher reuse distances may be needed. We also note that when the average number of neighbors exceeds 30, there are practically no interference issues which is due to the limited diameter of the networks leading to limited need of spatial reuse. All node nodes retransmit the packets within the first three relay slots.

In [4], we also show that a low reuse distance causes similar interference problems irrespective of network size. If data rates are adapted to the network connectivity a reuse distance of 4 seems optimal for all but the most connected networks, when nearly all nodes are neighbors. In [4] it is also suggested a new method for synchronized cooperative broadcasting and frequency hopping, which eliminate interference for a reuse distance of 3, thus increasing the network broadcast capacity by 33% as compared with synchronized cooperative broadcasting with a reuse distance of 4.

2.4 Performance Comparison with TDMA

In this section, we summarize our comparison of the network broadcast capacity obtained by SCB and traditional TDMA-based schemes published in [5] . The capacities are calculated for ad hoc networks with different connectivity levels. The comparison is made for broadcast traffic, which is a dominating type of traffic in many military networks. A uniform traffic distribution is assumed in the comparison, i.e., all nodes transmit an equal amount of broadcast traffic. In the comparison for SCB, we include both the cases when the CBS size is set to three and four, i.e., a reuse distance of three and four.

The TDMA-based network uses traffic adaptive Spatial reuse TDMA (STDMA). A centralized STDMA scheduler having all network information is assumed, i.e. it knows all path gains and total traffic load in all nodes, including traffic load from relaying. The STDMA scheduler can therefore deliver a very efficient schedule, close to an optimum one. Based on this schedule, which depends on the routing method, the network broadcast capacity can be calculated, see [5] for details.

We consider three different types of routing methods for STDMA. First, a tree-based solution, where each node (source) will generate a broadcast tree with itself as root. The trees are built using a greedy heuristic. Using such trees is efficient as it keeps the number of retransmissions low but they are difficult to maintain in mobile networks. The second routing scheme considered is MultiPoint Relay (MPR) flooding with default parameter settings. The third routing scheme considered is a more robust version of MPR flooding but with a higher overhead. As described in the OLSR RFC [6] , MPR flooding can be made more robust by increasing the MPR coverage radius. In default MPR-flooding the coverage radius is set to one, whether it for the more robust version of MPR flooding considered is set to two. Finally, STDMA combined with full flooding is included as a reference. Full flooding is very robust but has a high overhead because all nodes retransmit all messages.

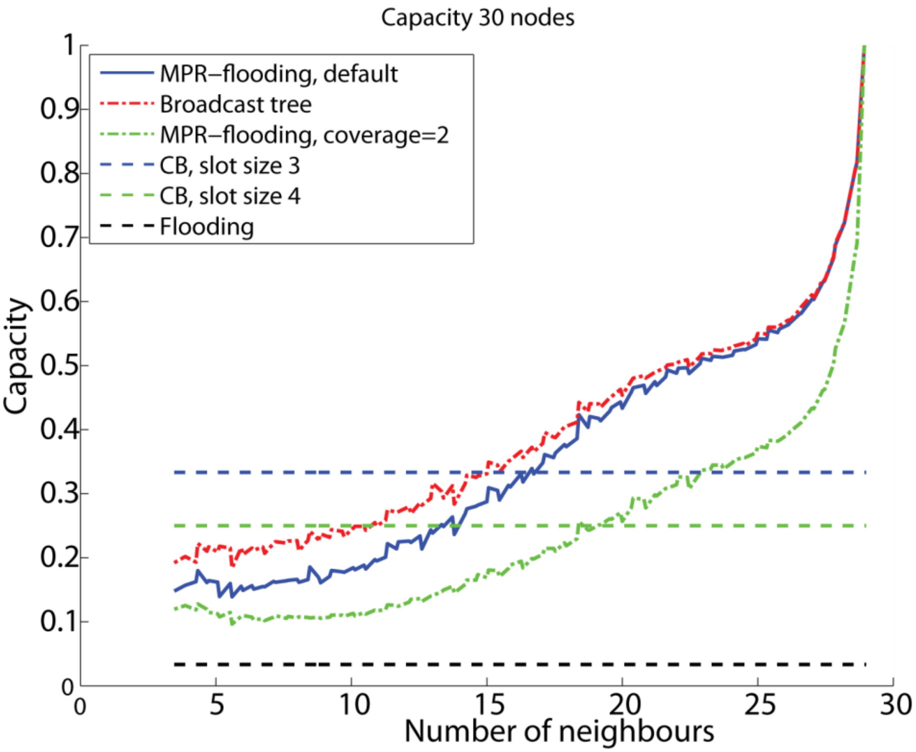

Figure 2.8 Network broadcast capacity comparison of MPR-flooding, broadcast tree, floodingand synchronized cooperative broadcasting in a 30-node network.

The results show that SCB, besides being robust, also has a higher network broadcast capacity than STDMA unless the networks are dense, see Figure 2.8. Especially when considering the robust version of MPR-flooding, a neighbor count of roughly 23 is needed to surpass the network broadcast capacity of cooperative broadcast. When the networks become very dense, most paths are two hops or less and in those situations the fixed reuse distance of the SCB scheme limits the achievable network broadcast capacity. In [5] it is also shown that the behavior is the same for larger network sizes with network broadcast capacity of the STDMA-based solution being even lower in the sparse networks.

As described earlier, the network broadcast capacity for SCB does only depend on the reuse distance and is therefore constant for all network sizes. The network broadcast capacity of MPR-flooding and broadcast tree-based solutions, on the other hand, are affected by the network size. In [5] the results show that as the network size increases, the proportion of networks where MPR-flooding has a higher network broadcast capacity than SCB decreases. Therefore, MPR-flooding is only efficient in large networks if the network is more or less a single-hop network. Note that even if the network capacity does not change with the network size, it still has to be shared between the nodes. That is, for a given network broadcast capacity less radio node capacity is left for each individual node in a large network than in a small network.

2.5 Dynamic Scheduling in Cooperative Broadcasting Schemes

Cooperative Broadcast Slots (CBS) are used to determine how packets are retransmitted in the network. However, so far in the report we have not discussed how to schedule the CBSs. If all nodes generate an equal amount of traffic, a round-robin schedule could be used (equivalent to traditional TDMA, but instead using CBSs). In general though, all nodes do not generate an equal amount of traffic. In such a case, it is important to dynamically allocate more CBSs to the nodes that currently need more transmission resources.

In [7] we have presented a decentralized scheduling algorithm that provides dynamic access to the cooperative broadcast medium in a traffic adaptive manner. In order to do this scheduling, we introduce specific administrative CBSs, which are used to transmit information about traffic load and allocated CBSs to all other nodes in the network, or at least all reachable nodes if the network is partitioned. Based on this information, the nodes determine how to generate and update the transmission schedule. The algorithm also handles merging of networks and the resolving of conflicting schedules. See [7] for a description of the algorithm.

The proposed algorithm is evaluated for mobile networks using a realistic terrain-based channel model and a demanding traffic model. The evaluations are used to determine the protocol's ability to adapt to varying traffic loads. So far, all evaluations shown in this report have been done for uniformly distributed broadcast traffic (equal load). The performance of our proposed algorithm using a non-uniform traffic distribution is evaluated in [7], and show that the performance is close to that bound even for sparse networks and high mobility. User data in the simulations are generated as both background traffic and session traffic. The background traffic is equal for all nodes and is in total 10% of the SCB broadcast capacity, representing some form of application sending status information. In addition to this, a number of broadcast sessions are generated with a single source, representing higher data rate services for a subset of the nodes.

We first investigate the Packet Delivery Ratio (PDR) for both the proposed dynamic scheduling algorithm and fixed scheduling for the 30-node networks. As can be seen in Figure 2.9, fixed TDMA scheduling does not perform well when the traffic is not equally divided between the nodes. When the number of sessions increases, traffic becomes more evenly distributed and the performance improves. However, as the variance of the number of sessions per node converge slowly, the packet loss is apparent even when there are more sessions than nodes.

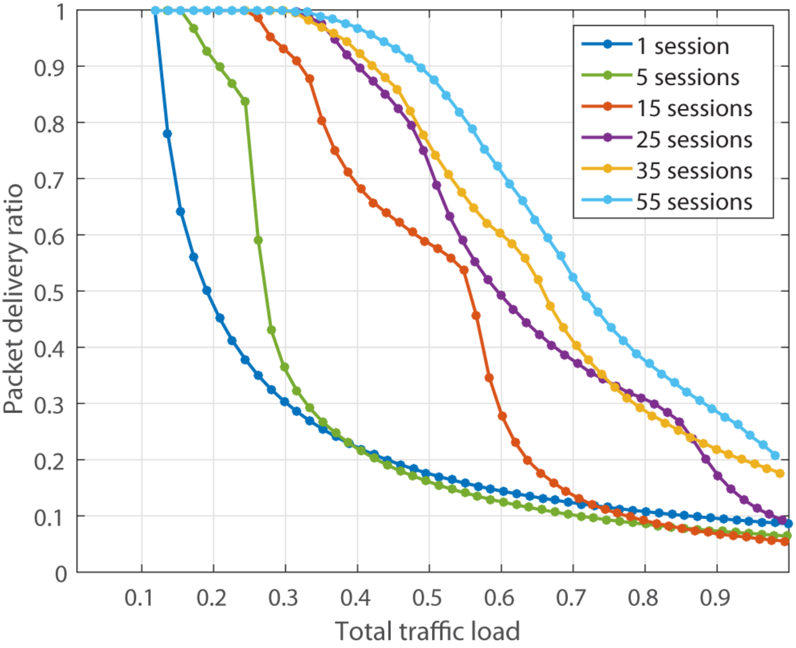

Figure 2.9 Packet delivery ratio for fixed scheduling in 30-node network. The total traffic load is given relative to the SCB broadcast capacity.

The performance of dynamic scheduling, seen in Figure 2.10, is much better than for fixed scheduling, especially for a single session at a time, with a broadcast capacity of almost 90% of the SCB broadcast capacity. With increasing number of sessions, the performance varies depending on the number of sessions. The main reason is quantization effects due to the fixed number of CBSs. For certain number of sessions and frame lengths, the quantization effects have a larger impact on the performance.

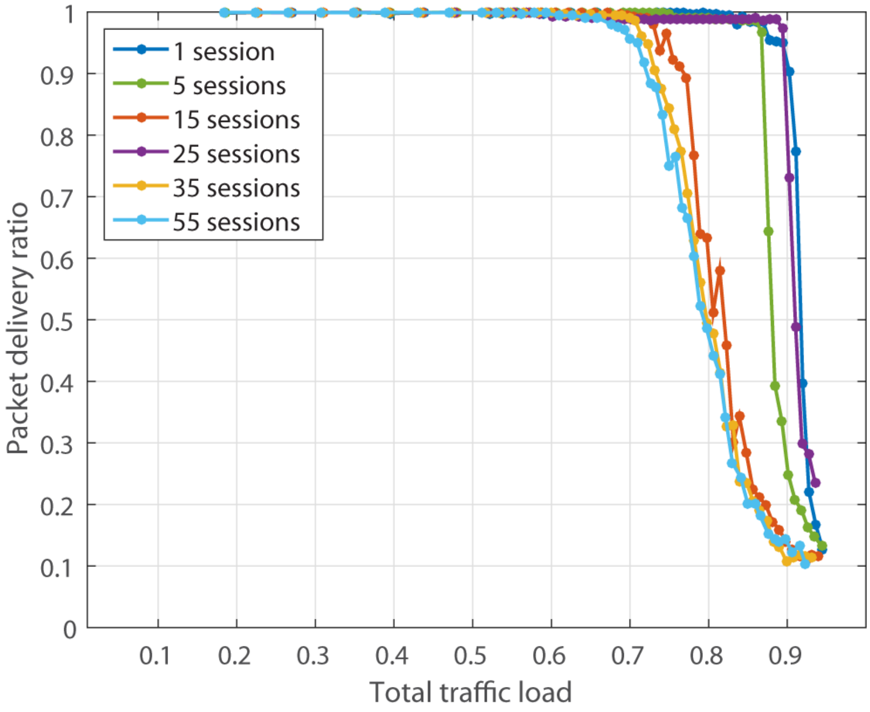

Figure 2.10 Packet delivery ratio for dynamic scheduling in 30-node network. The total traffic load is given relative to the SCB broadcast capacity.

Thus, the choice of frame length is clearly important. More specifically, a short frame length might result in insufficient traffic adaptivity. A longer frame length could reduce this problem, especially for the case where there are more sessions than the number of CBSs. A longer frame length on the other hand increases the overhead, and make the scheduling less responsive.

Robust broadcast communications in highly mobile ad hoc networks is a challenging area. High mobility in combination with a demanding propagation environment causes fast link variations that must be handled. The presented algorithm solves this challenge in a distributed and traffic-adaptive manner. The results in [7] show that the algorithm works in both 30- and 60-node networks and even when the network connectivity is low.

2.6 Evaluation in the Anglova Tactical Scenario

The behavior of wideband SCB-network is evaluated using Vignette 2 of the Anglova scenario [8][9]. Vignette 2 covers the deployment of the coalition forces, a battalion, into the operational zone. The task for the battalion is to stage an attack against a hostile force. The battalion consists of six companies: four mechanized companies with 24 vehicles each, one command and artillery company with 22 vehicles, and one support and supply company with 39 vehicles. Together, there are 157 vehicles, each of them being a network node. The mobility pattern is characterized by movements over a rectangular area of 13 km by 9 km mainly utilizing large and small roads, see Figure 2.11. The speed of the vehicles varies, with speeds up to 60 km/h on the main roads. Altogether, the Vignette 2 is 7800 seconds (130 minutes) long.

Figure 2.11. Trajectories of all nodes in Vignette 2.

The evaluation investigates the capability to deliver Battle Management System (BMS) traffic, including fast position information, see [9]. The BMS traffic is sent to the whole network and the requirement on the delay is 15 seconds. The position information is sent one hop only, every 3rd second, with a delay requirement of one second. Besides the BMS and position information traffic that is called basic traffic, extra traffic is added to be able to investigate the total traffic load the network can support.

In [9], SCB uses a wideband waveform (1.25 MHz) based on a frequency-hopping OFDM system. The investigation shows that the basic traffic can be very well supported. Also, that a considerably amount of extra traffic can be delivered at the same time. The main conclusion of the investigation is that for a relevant scenario, the BMS traffic including fast position information plus additional traffic, can be communicated within a battalion with only one wideband SCB network.

3 Multicasting by Efficient Flooding at the Network Layer of Mobile Ad Hoc Networks

As pointed out in [10] there is no “one size fits all” multicast protocol for efficient group communication in mobile military networks. The reference discusses multicast solutions at the network layer of the protocol stack. The reference further states that, since building and maintaining multicast trees are costly and error prone in mobile wireless environments, an efficient flooding protocol like Simplified Multicast Forwarding (SMF)[1] is the preferred candidate for group communication in many military scenarios. The main reasons are its robustness to high mobility and efficiency for scenarios where multicast receivers are located in close proximity of each other and where there is a high density of multicast receivers. This is often the case in military group communication scenarios at the tactical edge.

In this chapter, we briefly report on two studies that propose improvements to SMF. In section 3.1, we provide an overview on how SMF works as background information for the next two sections.

In section 3.2 a method for group communication utilizing UAVs is presented. More details of the work can be found in [11]. The main advantage with UAVs for group communication is the large footprint one transmission by the UAV can have. Hence, one transmission can cover a large portion of the network and consequently reduce the number of transmissions required by SMF to flood the network.

In section 3.3 the problem of limiting the flooding of SMF to a scope that is smaller than the whole network, is addressed. More details of this work can be found in [12]. SMF by default attempts to flood the whole network. Sometimes the multicast group is much smaller than the whole network (e.g., a company in a battalion sized network). For such groups it is beneficial to have a method that constrains SMF to only flood the portion of the network that covers the multicast group.

3.1 Simplified Multicast Forwarding

Simplified Multicast Forwarding (SMF) is an experimental RFC [1]. It is a well-known optimized flooding protocol that is one of the candidates for group communication support in modern mobile high data rate military radio systems. The motivation behind SMF is to provide robust multicast support in disruptive mobile wireless networks with a high density of multicast receivers (all or most of the users are interested in the group traffic). In such networks, building and maintaining a connected multicast forwarding tree is challenging due to high dynamics.

SMF utilizes two important building blocks; Duplicate Packet Detection (DPD) and reduced relay set. DPD is needed in multi-access wireless networks where the same packet can be received from more than one neighbor. The duplicated packet must be detected and not retransmitted. Reduced relay set is used to reduce the number of forwarders in the network to decrease the number or redundant transmissions. SMF aims to flood the group traffic to the whole network, and does neither need to maintain information about multicast group members, nor build a forwarding tree.

The idea behind the relay sets is to identify the minimum number of neighbors that must forward a packet in order to reach all two-hop neighbors (form a Connected Dominated Set CDS). Classic Flooding is defined as the simplest case of SMF where DPD is performed but no reduced relay set is used. This is very robust but less resource efficient solution. A more efficient solution, at the cost of robustness, is to calculate a minimum relay set. Many algorithms are proposed to calculate relay sets which yields different tradeoffs between redundant packet transmissions (robustness) and resource efficiency. Some of the algorithms are described as appendixes in [1].

3.2 Improving Simplified Multicast Forwarding using an Elevated Relay Node

A mobile wireless network could benefit from using an elevated network node as a communication relay and was studied in [11]. Elevated nodes typically have a higher probability for Line-of-Sight (LoS) communication with ground nodes than ground-to-ground communication. This can potentially increase the connectivity of a MANET. The cost is reduced spatial frequency reuse as a consequence of a larger interference radius. In this work we have studied how Simplified Multicast Forwarding (SMF) can be used with an elevated forwarding node (UAV).

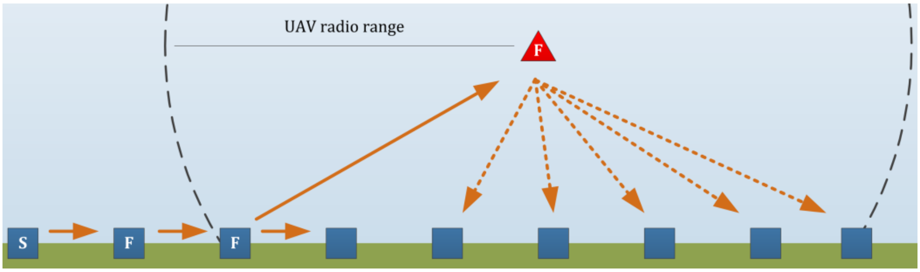

Figure 3.1: SMF distribution in a MANET with an elevated network node. The elevated node is both a powerful and a vulnerable SMF relay.

In terms of optimization of network resources, the usage of UAV will play an important role especially in terms of unicast and multicast traffic usage. For unicast traffic, an elevated network node will be advantageous at low data traffic volume. However, as the traffic volume approaches the capacity of the elevated node's radio channel, the reduced possibility of spatial reuse will limit the total network capacity. This quantitative impact depends mainly on the topology, the node density of the network, and the traffic patterns.

Many transmission technologies employ adaptive link modulation, balancing a high data rate against less robust modulation. Hence, long transmission range is achieved at the cost of lower network capacity. For multicast and broadcast, high robustness is normally selected. It is motivated by improved assurance to reach all the receivers within the radio's proximity, at the cost of reduced data rate.

Sending unicast packets to one or a few receivers using high data rate modulation can in many situation be more effective than broadcast/multicast. However, with increased node density and number of receivers, the required unicast transmissions time will increase far past the required multicast/broadcast transmission channel time.

Elevated network nodes will likely have an important role in future communication networks. However, their presence might reduce the packet delivery robustness for both data traffic and routing. An elevated network node participating in a MANET with ground nodes will have many more neighbors than the ground nodes. In case of Optimized Link State Routing (OLSR)[13], an elevated node will likely be selected as Multi-Point Relay (MPR) by the covered ground nodes. As a consequence, many of the ground nodes will end up not having redundant MPRs. Adding to this problem, multicast and broadcast transmissions are not as reliable as unicast, due to the lack of packet acknowledgment, and thus Automatic Repeat reQuest (ARQ) at the Medium Access Control (MAC)-layer. Consequently, if the elevated node fails in receiving a packet from a ground node, there is a risk that a large fraction of the elevated network node's MPR selector set will never see the packet, as illustrated in Figure 3.1 and Figure 3.2. Figure 3.2 shows the difference of packet transmissions between nodes at the ground with an elevated node/UAV(green color) and without an elevated node/UAV (blue color). With UAV, a large portion of the ground nodes selects the UAV as an MPR, and thus less redundant transmissions will occur at the ground. As a result if a UAV fails to transmit the packet, a large ground area will not receive the packet due to the failed transmission and reduced redundancy at the ground.

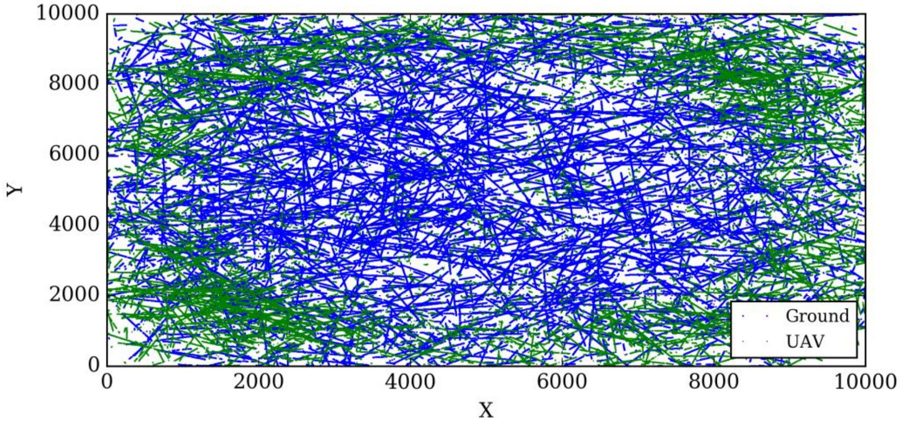

Figure 3.2: Positions of transmission events using a UAV (green color) and without a UAV (only at ground, blue color), illustrating the “black hole” beneath the UAV.

Elevated nodes might both reduce the problem of packet collisions and suffer from an increased risk of the same. Assuming an IEEE 802.11 MAC layer, if the nodes are all within radio range, only one will transmit and no collision occurs. On the other hand, nodes dispersed over larger areas will not be within radio range and the hidden node problem increases if CSMA/CA is used at the mac layer. Hence, the benefit of elevated network node follows the area of coverage along with the number of receivers within the same area.

We analyze the effect that an elevated network node has on the dissemination of multicast packets using SMF. Second, we propose to improve the dissemination of multicast traffic by changing the forwarding from multicast to unicast from a source to the elevated network node, and then further start the SMF forwarding from the elevated network node. Unicast is less robust against mobility, thus we finally propose buffering and potentially retransmitting the unicast packet as an SMF-packet from the source to improve the reliability of the packet dissemination.

3.2.1 Methods for Improving MANET Group Communication

Four different methods are described and compared. These are called *Ground*, *UAV*, *Unicast* and *Buffer unicast*. The normal behavior and performance of the SMF protocol in a ground-based MANET (*Ground*) serves as a baseline in our study. Using this baseline, we investigate the effect of introducing an elevated network node into the MANET using standard SMF, focusing on the dissemination of multicast packets. These results are labeled *UAV*, reflecting the possibility of a highly mobile elevated relay node.

We propose improvements to the standard SMF forwarding by adapting it for better use with an elevated network node. The improvements are labeled *Unicast* and *Buffer unicast*. They both use unicast as the forwarding mechanism from the source to the elevated network node and SMF from the elevated network node. The two methods differ in the reliability of the delivery to the elevated network node.

Unicast: The source encapsulates the multicast packet in a unicast header and sends it as unicast up to the elevated network node. The elevated network node decapsulates the multicast packet and forwards it using SMF, as shown in Figure 3.3. This method shares many similarities with [14] but instead of flooding, the multicast forwarding uses SMF.

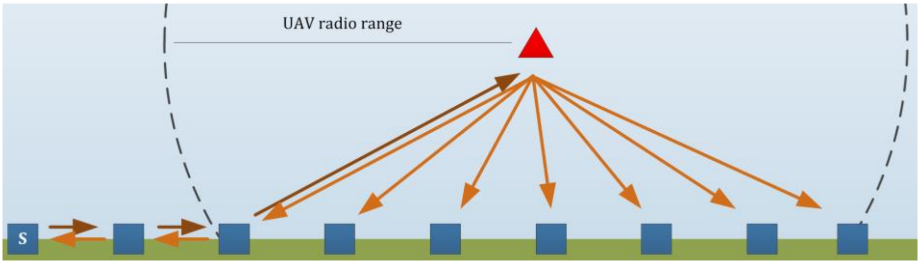

Figure 3.3: Source with a connected link to the elevated network node.

In situations where many nodes compete for radio resources, the likelihood of collisions increases. Multicast and broadcast traffic is particularly exposed to collisions, as senders have no methods to detect collisions. Many MAC-layer implementations, such as the popular IEEE 802.11 implements link-layer ARQ for unicast transmissions. The sender can thus infer a collision and resend the packet. Hence, unicast can increase the probability of successful transmission.

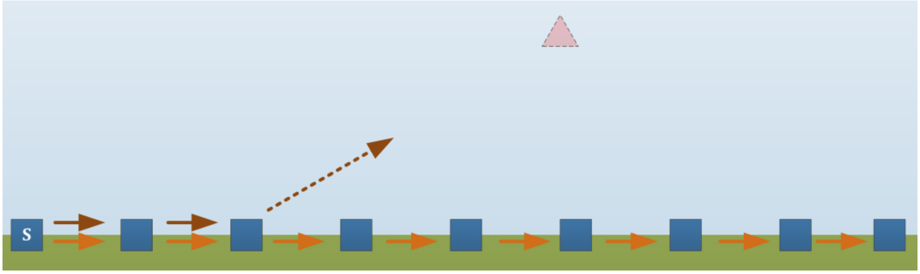

Figure 3.4: Source with a broken link to the elevated network node. The source sends SMF at ground.

Buffer unicast: An extension to *Unicast*, where the source buffers the multicast traffic for a defined time. The source waits to hear the buffered multicast packet as it is broadcast by the elevated network node until a timer expires. If the timer expires, the source itself sends the buffered data as multicast using SMF. Having the buffer will improve the robustness for situations where the unicast path up to the elevated network node or the multicast path from the elevated network node is disrupted, as illustrated in Figure 3.4.

3.2.2 Simulation Study

The following subchapters describe the result of the four described methods. The first test represents a situation when the source is situated within 1-hop from the UAV (Single-hop), while the second test is when the source is located at least 2-hop from the UAV (Multi-hop). The source and the UAV do not move during the tests. The other nodes move with a random direction at 10 m/s. The figures (Figure 3.5 and Figure 3.6) show packet delivery ratio as a function of the number of mobile nodes within a predefined area. More detailed information can be found in [11].

3.2.2.1 Single-hop

The use of an elevated network node increases the packet delivery (Figure 3.5), especially for low node densities. The positive effect of the UAV is due to the increased ground coverage of the UAV. The results of packet delivery for the baseline (*Ground*) and SMF with UAV (*UAV*) converges as the number of ground nodes increases. At high node densities the network is more connected at ground, and the ground-based SMF forwarding can propagate over many alternative paths between any two nodes. This robustness results in high packet delivery, thus reducing the performance gap compared to the use of the elevated node.

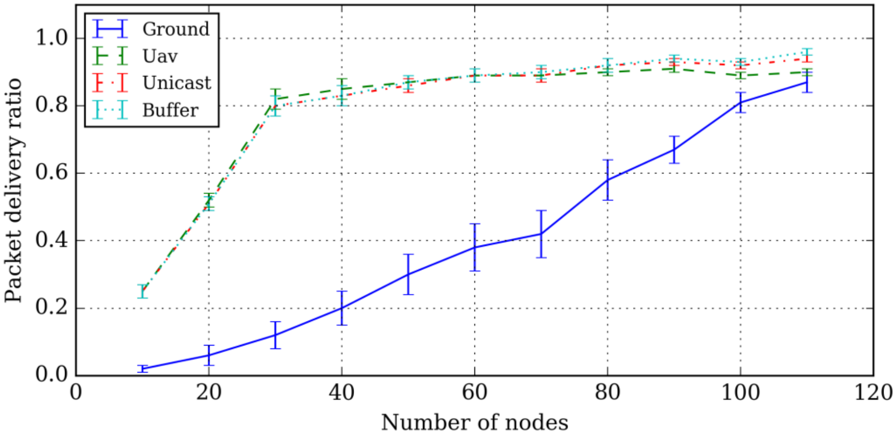

Figure 3.5: Packet delivery ratio in the single-hop scenario.

Neither of the methods obtains a 100% packet delivery. At high node densities, all of the methods approaches Packet Delivery Ratio (PDR) of 0.9. Earlier work evaluating SMF under different node densities and traffic loads has observed similar results [15]. The authors observed that forwarding packets using Source based MPR suffers a 10% loss compared to flooding, even when the network is fully connected. Hence, as the number of nodes increases, SMF approaches its achievable PDR.

Unicast and *Buffer unicast* achieve slightly higher *PDR* than *Ground* and *UAV* at high node densities. The main reason is that these methods unicast packets up to the elevated network node. Hence, they give each packet multiple transmission attempts to reach the elevated network node.

A reliable link up to the elevated network node is especially important when the number of SMF forwarding nodes selected by the elevated network node increases. In this situation, the traffic increases, and the collision likelihood is higher at the UAV than at any ground node, due to the hidden node effect. This effect of the ARQ of the link for *Unicast* and *Buffer unicast* is seen as the node density increases.

3.2.2.2 Multi-hop

In this performance test, the source is located beyond the direct UAV link range. It still remains immobile during the simulations. Thus, we are guaranteed that there are at least two hops between the source and the UAV, which allows us to compare how the results change with a longer path between the source and the UAV.

The forwarding methods show larger variations in the PDR performance (Figure 3.6) than observed with a direct link between the source and the elevated network node. The added robustness of the *Unicast* and *Buffer unicast* methods becomes more evident with a longer distance between the source and the elevated network node. Similar to the previous test (Single-hop), the UAV is the main component that improves the packet delivery. However, contrary to the previous test, the *Unicast* and *Buffer unicast* methods perform better than the others as the node density increases. Since the source is positioned minimum two hops away from the UAV, the connectivity between the source and the UAV will be poor at low node densities. As the node density increases, more alternative paths are provided, but the routing protocol needs to discover path changes and perform rerouting. A link is timed out after six seconds. If a path is stale, packets are dropped until a new valid path is established. In this situation, *Buffer unicast* will give otherwise lost packets a second chance.

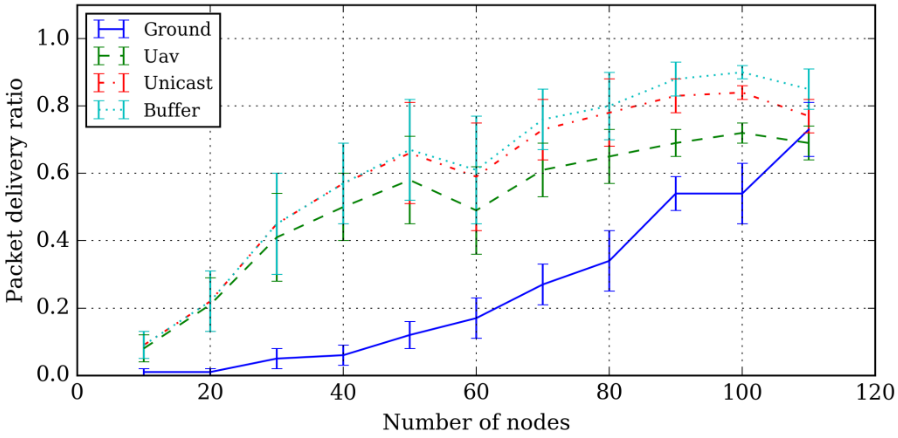

Figure 3.6: Packet delivery ratio in the multi hop scenario.

3.2.3 Summary of Improving Simplified Multicast Forwarding using an Elevated Relay Node

The benefit of utilizing an elevated network node is especially evident at low node densities.

Four forwarding methods are evaluated. The most complex method that combines unicast and buffering is preferable. The main reason is improved probability of reaching the elevated network node at low cost, resilience against loss of unicast packets up to the elevated network node, and benefits from the elevated node’s large coverage.

At high node densities, the ground-only multicast forwarding (SMF) achieves the same packet delivery ratio as the methods based on an elevated node, due to redundant forwarding used by SMF. Even so, the ground-based forwarding costs slightly more.

3.3 Limiting the Flooding of Simplified Multicast Forwarding to a Defined Scope

As more high data rate radios are introduced in the area of operation, it is a debate how the network architecture should look like. How large should the network be in order to best deal with the tradeoff between efficient end-to-end connections in a larger network, efficient use of the large (e.g., 1.25MHz or 5MHz) frequency bands required by these radios, and the available network capacity to the warfighter? In this work we study an architecture where a high data rate radio network is deployed to cover a larger military unit (e.g., a battalion) on one frequency band. Potential advantages with this architecture are efficient end-to-end connections throughout the network and a need for fewer frequency bands compared with a situation with smaller networks.

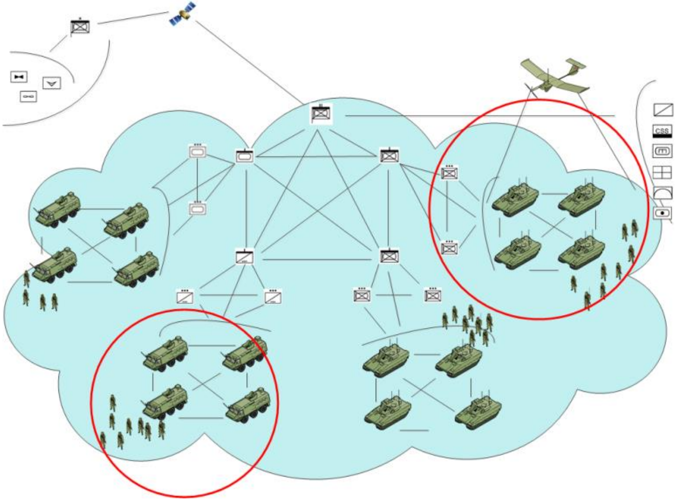

Figure 3.7 This figure shows a high data rate radio network spanning a battalion. Two example multicast groups are shown, a company group and a platoon group.

This network architecture must continue to support the important traffic types for the lower military echelons in an efficient manner. For example it should be possible to efficiently distribute group communication services such as friendly force tracking and push-to-talk voice to smaller groups than the whole network (e.g., a company or platoon in Figure 3.7). If the network covers a large military unit such as a battalion and the data is meant for one company, it is not resource efficient to flood the data to the whole battalion as standard SMF (and also synchronized cooperative broadcast) would do. Therefore, in this work we discuss methods to limit the forwarding of the group traffic to the intended recipients while preserving robustness by utilizing SMF as the basic carrier of the group traffic. The following subsections gives a summary of the study, see [12][16] for more details.

3.3.1 Constraining SMF’s Flooding to a Defined Scope

We need a method to limit the flooding of SMF to a small segment of the network (e.g. a company, platoon etc.). The methods must be able to control the range of SMF, i.e. to set an SMF-scope for the flooding. The interested receivers of a group communication service create a multicast group. Classic SMF does not pay attention to the multicast group; instead it floods the information to the whole network, implicitly reaching all the group members. It is necessary to introduce some notion of group membership to SMF in order to constrain the flooding and stop it when all group members are covered. We do this by introducing the notion of SMF-scope to SMF.

For military scenarios the following two types of multicast groups are very suitable for using SMF limited to a SMF-scope as the forwarding technique:

Organizational groups: We call multicast groups that reflects the military organization for organizational groups. These groups represent all members of a specific part of a military organization e.g., all units in a specific squad, or units in a specific mission.

Geographic multicast groups: With geographic groups the nodes’ location decides if they are part of the multicast group or not. A defined area on a map defines the group and all nodes that are positioned inside the defined area, creates the group. A geographic multicast protocol e.g. [17] inherently supports geographic scope.

We choose organizational multicast groups as the main use case for the work describe here since these types of groups are expected to be used extensively in military operations today and should be supported efficiently also in a new network architecture as exemplified in the scenario used for this work (see Figure 3.7).

The main reasons for introducing an SMF-scope to the SMF protocol are to preserve radio resources, and to not disturb network nodes that are not interested in the group traffic. Network resources are scarce in mobile military networks and thus resource efficient data dissemination methods must be addressed. Limiting the scope of traffic dissemination is also a security achievement since this reduces the number of nodes that are exposed to the data. In the following subsections, we describe different methods to set the SMF-scope size.

3.3.1.1 TTL to set the SMF-scope

A straightforward method to set the scope of SMF to a smaller size than the whole network is to set a limit on Time to Live (TTL) for the IP packet in the network. The disadvantage with this method is the difficulty to predict the correct TTL to make sure that all nodes in the multicast group receive the traffic and at the same time limit the flooding to a minimum. The number of hops required to reach all members in the group will differ in different terrain (e.g., flat, urban, forest, mountains) and for different operations (e.g. convoy, combat). Furthermore, the source can be on the edge of the network that represents the group, or in the center.

The accuracy of this technique can be improved if SMF can access the topology database of the unicast routing protocol.

3.3.1.2 Administrative SMF-scope with aid of TTL

Another technique is to combine TTL limit with administrative scoping [18] as used in the Internet. With this method, the forwarding nodes that are part of the multicast group will not decrement the TTL. The TTL decreases first when it is being forwarded by a node that is not part of the group, and stops when TTL is zero. This method is robust for some mobility and challenging terrain but cannot handle a partitioning of the multicast group where the network distance between the group segments exceeds the set TTL.

3.3.1.3 Administrative SMF-scope with aid of MultiPoint Relays

It is also possible to modify the forwarding rules of SMF’s forwarding nodes with administrative scope technique. We use the MPR algorithm of the Optimized Link State Routing Protocol (OLSR) [13] as an example. All MPRs know their 1-hop neighbors and 2-hop neighbors. In addition to the standard SMF forwarding rules, each MPR investigates whether itself and/or a 1-hop neighbor and/or a 2-hop neighbor are members of the multicast group.

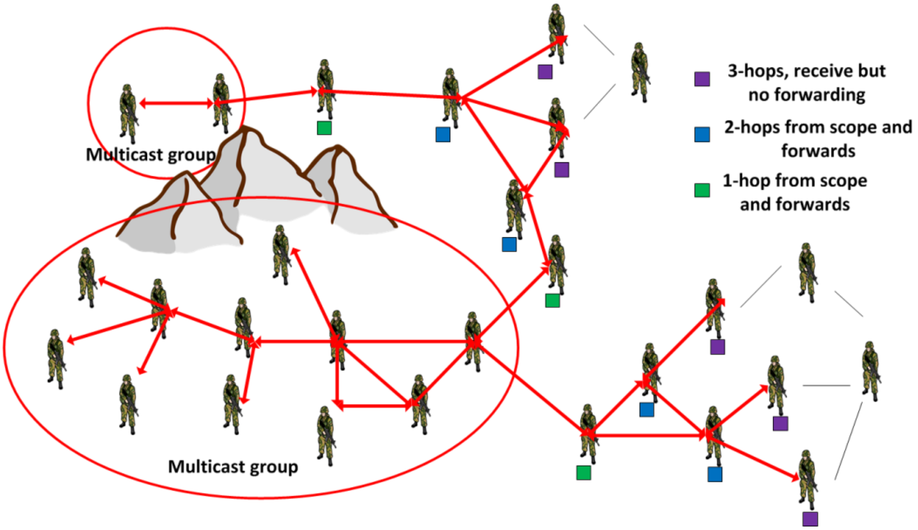

Figure 3.8 Two partitions of the same scope is reconnected when MPRs forward scope messages to scope neighbors within 2-hops.

If the goal is to optimize for resource utilization and not allow the group traffic to be forwarded by any non-group members then the forwarding rule is; the MPR forward traffic only if the MPR itself is member of the scope. If the goal is to have more robustness, then relay support by non-multicast members might be needed. In this case the forwarding rule can be; the MPR's forward traffic if either the MPR itself is a multicast member or a 1-hop or 2-hop node is a multicast member. This method improves the robustness as it is able to connect multicast members that can be up to 5 hops apart as illustrated in in Figure 3.8. However, this comes at the cost of potentially flooding the traffic to many non-member nodes.

3.3.2 Tailored SMF in Conjunction with Connectionless Multicast

The presented methods to tailor the SMF-scope vary regarding flexibility, dynamics and robustness. In very challenging terrains or in situations where the topology of the group members will change much during the operation (the group need to split up and/or mix with other units) the SMF-scope must be very large to ensure that the whole multicast group is covered by the SMF flooding. This is not very efficient and we want to find better methods to provide delivery to the whole multicast group.

We propose one method that allows the multicast group to be served by several smaller SMF-scopes and where the SMF-scopes are interconnected with added forwarding logic. The role of SMF-scope leaders is proposed. These leaders assist in the interconnection of multiple SMF-scopes. The proposed method shares many similarities to MANET protocols build on clusters such as Hierarchical OLSR [19].

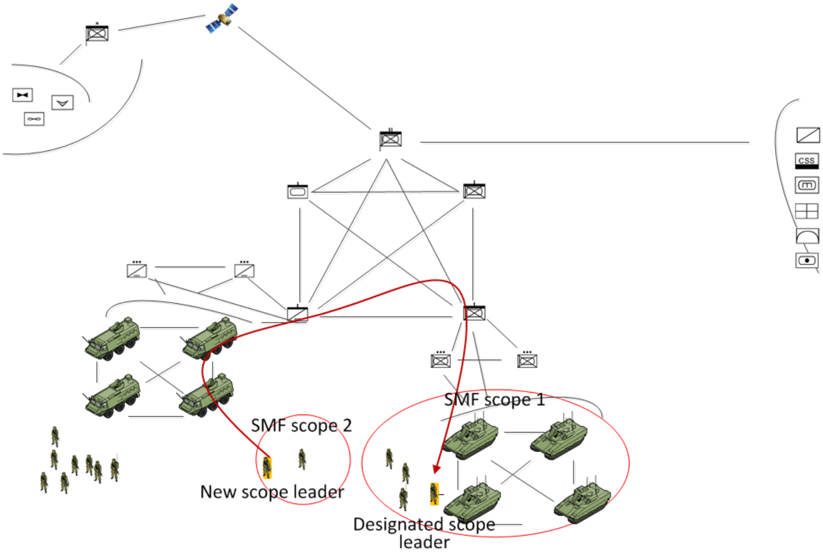

Figure 3.9 A new SMF-scope segment elects a new leader and connects back to the designated SMF-scope leader.

It is assumed that the multicast group is fully connected when the traffic to the group starts. The node that is chosen as the first SMF-scope leader will become the designated SMF-scope leader. SMF-scope leaders are responsible for disseminating heartbeat messages to the SMF-scope members to keep track of SMF-scope connectivity. The heartbeat messages must have the same range as the flooding of the group traffic. One plausible implementation is to use “Administrative SMF-scope with aid of TTL” as described in section 3.3.1.2 for the heartbeat messages. The group traffic is forwarded with the same technique inside each SFM-scope segment.

When some members of the SMF-scope stop receiving the heartbeat messages an additional SMF-scope leader is elected. The new scope leader is responsible for contacting the designated scope leader (e.g., via unicast) as shown in Figure 3.9. The group of SMF-scope leaders forms an overlay network and can use Explicit Multi-unicast (Xcast [20]) to forward the group traffic between them. Xcast encodes the address of the receiving group (the SMF-scope leaders) in the packet headers and uses the unicast routing table to make the necessary routing decisions. Upon reception of the Xcast packets, each SMF-scope leader is responsible to forward the group traffic inside its SMF-scope. This technique is robust and can support a dynamic group topology at the cost of the added overhead to establish and maintain the overlay network between the SMF-scope leaders. See [12] for more details.

3.3.2.1 External sources and receivers

The method described above can easily be extended to support a wider range of group types where external sources and receivers that are not part of the organizational group, which creates the original multicast group, can also join the group. In military operations there are situations when it is beneficial for an external source to send data to a specific military unit. Examples are alarms, and orders. It is also of interest to allow external nodes to join the multicast group in order to receive information from a military unit. One example can be a MEDEVAC team that wants to subscribe to friendly force tracking from the company with the wounded soldier. These external multicast members can be quite far away from the rest of the group.

In order to support forwarding of group traffic to external sources and receivers in the multicast group, with the technique described in section 3.3.2, the external nodes are simply treated in the same manner as SMF-Scope leaders. Thus, the external nodes are included in the Xcast overlay network (Figure 3.10). Some method is needed to announce the existence of the multicast group to the external nodes. This can be solved with e.g., static information, flooding or a central service registry.

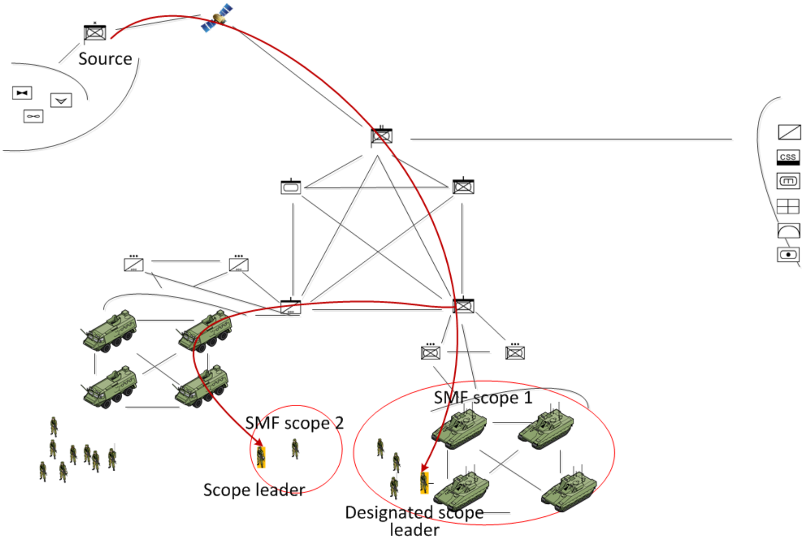

Figure 3.10 An external source sends group traffic to a multicast group represented by two SMF-scope leaders using connectionless multicast. The source knows the address of each SMF-scope leader.

When scoped SMF in conjunction with Xcast is used as described in this section. The scenario is one that could potentially be served similarly well with a traditional mesh-based multicast protocol. It must be further studied how the SMF and Xcast solution performs compared with such protocol (e.g., On-Demand Multicast Routing Protocol (ODMRP) [21]).

3.3.2.2 Multicast group connectivity over heterogeneous mobile military radio-networks

The SMF-scope and Xcast method can also be used to provide support for group communication across a heterogeneous mobile military network. The external multicast members mentioned in section 3.3.2.1 might sometimes be connected to another radio network that cannot be reached by the SMF protocol in the battalion radio network example in Figure 3.7. Another example is a connected coalition network where each partner provides friendly force tracking distributed with SMF in their national radio networks. There is a need to share the friendly force tracking between the partners. For both of these situations Xcast can be used to connect the multicast members in different networks. Xcast rely on unicast routing to forward the traffic, thus if unicast routes are available in the heterogeneous network, the Xcast service to connect the designated SMF-scope leaders of each SMF-scope and external receiver/sources, can be made available.

3.3.3 Conclusion of the SMF-Scope Study

Several methods are proposed for efficient support of traditional group services such as friendly force tracking and push-to-talk voice to receivers that make up a smaller group than the whole radio network size. The presented technique utilizes several small SMF-scopes interconnected by the aid of a network of SMF-scope leaders. The technique requires some network control traffic to work. However, when the framework is established, it provides a flexible solution that can also be used to support group communication across different networks in a heterogeneous network scenario.

It remains to be seen how well the proposed methods perform in a typical military mobile network. Comparison of the overhead and robustness of the different scoping methods as well as simulation of the SMF-scope leader design in a heterogeneous network environment is required to better understand how well the proposed design works.

4 Conclusion

We study properties and improvements of two of the most interesting technologies for forwarding of group traffic in mobile military ad hoc networks, Synchronized Cooperative Broadcast (SCB) at layer 2 and Simplified Multicast Forwarding (SMF) at layer 3.

We investigate SCB in a tactical broadband battalion network. The broadcast capacity of an SCB network is inversely proportional to the reuse distance. The reuse distance is the minimum number of network hops between two nodes simultaneously transmitting different packets and is an adjustable system parameter in SCB. We show that a reuse distance of four gives a good compromise between packet delivery ratio and broadcast capacity.

Furthermore, our results show that SCB, besides being robust, also has a higher network broadcast capacity than traditional TDMA-based schemes unless the networks are so dense (many neighbors) that only one or two retransmissions are required for the broadcast. Comparing network broadcast capacity for different network sizes (i.e., number of nodes) show that the benefits of using SCB increase with the size and area coverage of the network. The network broadcast capacity remains constant for SCB, whereas it decreases with network size for the TDMA-based scheme.

In addition, we have developed algorithms that dynamically adapt capacity to the changing traffic loads of the nodes. The algorithms provide significant higher capacity in mobile networks compared to basic static algorithms, both in dense and sparse networks

The SCB technology can provide sufficient robustness in tactical radio networks. This has been demonstrated by analyzing how SCB meets battle management system traffic demands in a tactical scenario. The scenario describes a mechanized battalion of 157 nodes preparing for battle. A main conclusion from the assessment is that the required battle management system traffic, including fast positioning, can be transmitted with high reliability without overloading the network. We also observe that only one broadband SCB network segment is sufficient to serve traffic from all the nodes of the battalion.

We have also investigated SMF and proposed improvements to enable the protocol to take advantage of elevated relays when these are present in the network. Forwarding with the aid of UAVs is beneficial in situation when the majority of the ground nodes are multicast members. SMF used in conjunction with elevated relays is an efficient method to distribute traffic to such groups since much of the group can potentially be covered with one transmission. The benefit of the elevated node comes at the cost of reduced robustness. To both achieve robustness and optimization we investigated different schemes to show the difference in robustness. The method that encapsulate the multicast traffic and unicasts the multicast traffic to the UAV, combined with ground based SMF forwarding as a backup if the source have not received the packet after a timeout, showed the best result.

In addition, we have proposed modifications of SMF to reduce the flooding of SMF to a defined scope that is smaller than the whole network. The purpose is to introduce some flexibility to SMF to also be efficient for smaller co-located multicast group (e.g. a company in a battalion-sized network). We also propose a protocol that uses a combination of SMF with a defined scope and connectionless multicast (e.g., Xcast) to further increase the flexibility of SMF. This latter protocol can also be used to support forwarding of group traffic to interested external nodes that are located some distance (in number or radio-hops) away from the center location of the group (e.g. Brigade HQ, cooperating forces from another military branch). We also believe that this technique can be used to support group communication end-to-end over different transmission technologies in a heterogeneous mobile military network.

SCB and SMF have both their pros and cons. For robust and efficient transport of group traffic internal to one transmission technology, then SCB is likely the solution to be preferred. However, SCB does not work across different radio technologies. Hence, if there is a need for more flexibility regarding the support for group traffic across different transmission technologies, then modified SMF in combination with Xcast is the likely preferred solution. Future work, in this setting, could be to design and evaluate a routing method enabling SCB being run isolated in each homogeneous network, but routing functionality to interconnect the SCB radio networks.

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