Routing Designs for Tactical Heterogeneous Networks

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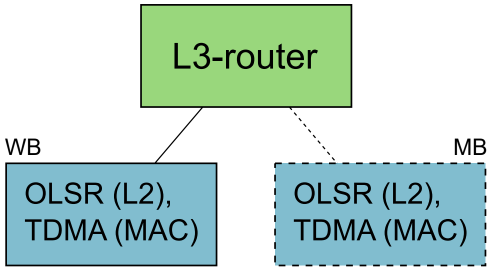

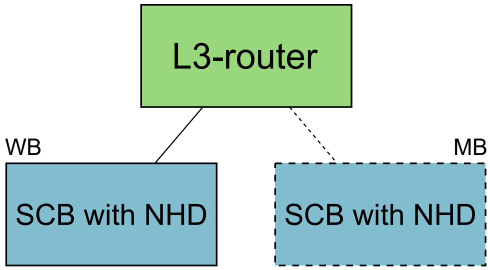

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Abstract

In military units of the size of a brigad or a battalion, several radio networks are often needed to be interconnected into a heterogeneous network. These interconnections can be designed in many different ways.

In this report, different designs to interconnect radio networks based on OLSR routing at OSI layer 3 were investigated. The goal of the design was to keep the overhead generated by the OLSR control traffic low, while at the same time maintaining a high packet delivery ratio.

For each radio network, two setups were used. In the first, the waveforms used Synchronized Cooperative Broadcast (SCB) to which a devised neighbourhood discovery procedure was integrated. In the second setup, the waveforms used OLSR on OSI layer 2 and TDMA at the MAC layer. To accomplish the interconnection, OLSR and modified versions of OLSR at OSI layer 3 were analysed. The results showed that the overhead was reduced considerably by introducing the OLSR modifications. In general, the setup with waveforms based on SCB worked better than the OLSR and TDMA setup.

Keywords: ad hoc networks, multiple interfaces, neighbourhood discovery, SCB, OLSR, routing, heterogeneous networks

Sammanfattning

I militära enheter (t.ex. brigader och bataljoner) är ofta radionätverken heterogena då olika typer av radionätverk behöver kopplas samman. Dessa sammankopplingar kan göras på många olika sätt.

I denna rapport undersöks olika metoder för att sammankoppla radionätverk baserade på OLSR-routing på OSI lager 3. Det övergripande målet var att hålla overheaden som genererades av OLSR-kontrolltrafiken låg och samtidigt bibehålla en hög andel levererade paket.

De utvärderade radionätverken var baserade på två olika typer av vågformer. Den första typen använde synkroniserad kooperativ broadcast (SKB) ihop med en metod för att skapa information om nätets topologi. Den andra typen använde OLSR på OSI lager 2 och TDMA på MAC-lagret. För att åstadkomma sammankopplingen på OSI lager 3 analyserades OLSR och modifierade versioner av OLSR. Resultaten visade att overheaden kunde reduceras avsevärt med hjälp av OLSR-modifieringarna. Generellt fungerade det heterogena radionätverket bättre med vågformer baserade på SKB än med vågformer baserade på OLSR och TDMA.

Nyckelord: ad hoc-nät, flera interface, nättopologi, SKB, OLSR, routing, heterogena nät

Contents

1 Introduction

Whenever different types of single networks are connected, a so-called heterogeneous network is formed. The single networks can be a various kinds. In this report, the focus was on mobile ad hoc networks where local transmissions are independent of a fixed infrastructure and nodes communicate with multi-hop connections through the network. This type of radio networks is dynamically self-configuring and can function autonomously when no connections with other networks are available. Nevertheless, it is a limit on how large a single flat ad hoc network can be. It depends among other things on underlying network technology, bandwidths, and what type of traffic the network needs to support. For larger military units (e.g., brigades and battalions) several flat networks is often needed to be interconnected into a heterogeneous network. These interconnections can be configured in many ways.

The study presented in this report is a continuation of a work from last year on multi-layer OLSR designs for heterogeneous networks, where different solutions to interconnect sub-networks based on OLSR routing at OSI[1] layer 3 (L3) were investigated [1]. In last year's work, the networks used TDMA and OLSR as network technology. In this years study, one focus was on also being able to include Synchronized Cooperative Broadcast (SCB) in the investigations. SCB is a relatively new network technology, increasingly used for many types of networks and scenarios. SCB provides robust multi-hop communication with low overhead and is particularly efficient for broadcast traffic. Integrated with SCB, a neighbourhood discovery (NHD) mechanism was devised and implemented. Networks having NHD integrated with SCB works as a OSI layer 2 waveform and have the capability of delivering network topology information to OSI layer 3. Such networks can therefore also be interconnected based on OLSR routing at OSI layer 3 (L3). Moreover, the different OLSR modifications from [1] were explored further in order to increase the routing efficiency. The ambition is a routing solution for a Brigade, however, for the assessments in this study a smaller military unit consisting of four companies were used.

The rest of the report is organized as follows. In order to make the report self-contained some parts from [1] is repeated. Chapter 2 briefly presents the different networks that are tested, SCB and OLSR. In Chapter 3 the OLSR modifications and NHD are described. Chapter 4 describes the simulation setups. In Chapter 5 the results from the simulations are presented. Finally, Chapter 6 concludes with the findings of the study.

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[1] The open systems interconnection model (OSI model) is a conceptual model consisting of seven layers that standardises the communication functions of a telecommunication system

2 Background

The first section of this chapter presents Synchronized Cooperative Broadcast (SCB). SCB is a relatively new network technology that increasingly is being used for many types of scenarios. SCB was used in one of the waveforms in this study. The second section describes the Optimized Link State Routing (OLSR) protocol. All the routing protocol used throughout this study are based on OLSR.

2.1 Synchronized Cooperative Broadcasting

Synchronized Cooperative Broadcast (SCB) is designed for robust broadcast communication in mobile ad hoc networks [2, 3]. One or several separate broadcast streams are managed using cooperative relaying and an underlying TDMA structure with separate sets of time slots scheduled to each source (broadcast stream). All nodes that receive a new packet in a time slot, simultaneously retransmit it in the next time slot that is scheduled to the same broadcast stream. For each broadcast stream, the protocol groups D time slots to a unit, which we call a cooperative broadcast (CB) slot with size D. The CB slots are grouped into repeating frames, as shown in Figure 2.1. The CB slot size is four in the example in the figure. Note that a packet can be transmitted D hops from the source node within one CB slot, but with the next CB slot scheduled for the same broadcast stream, it propagates another D hops further out in the network and so on until all nodes are reached. The CB-slot size D is also equal to the *reuse distance*, which describes the minimum number of hops between two nodes that can transmit different packets simultaneously.

In the CB slots allocated for a source node, only packets originated from the same source node are handled. When the source node transmits a new packet it will do so in the first time slot of its CB slot. All nodes that receive a packet, simultaneously retransmit the packet in the following time slot in the same CB slot. This procedure is repeated until all nodes in the network have retransmitted the packet once. The reception of multiple copies of a packet in a time slot is assumed to be handled by the receiving nodes similarly to how multipath propagation is handled.

2.2 OLSR

The Optimized Link State Routing (OLSR) protocol is a proactive link-state routing protocol, optimized for mobile ad hoc networks. In the evaluation, an implementation was used in the simulator, which is from now referred to as

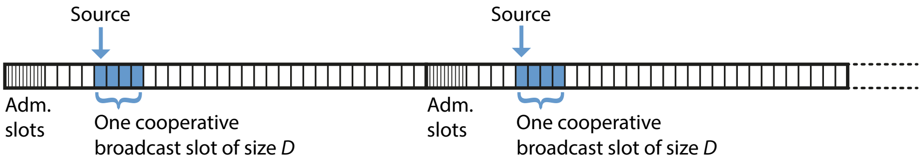


Figure 2.1: Example of SCB with administrative time slots for sending control information.

standard OLSR, abbreviated as *OLSR-STD*. The implementation follow RFC 3626 [4] which describes the protocol OLSR. For broadcast traffic, the multi-point relay (MPR) flooding mechanism of OLSR was of interest, originally designed for efficient flooding of OLSR control messages. The messages are relayed between nodes by the MPRs. Instead of all nodes a subset of the nodes in a network is selected as MPRs. The basic idea is that each node selects a subset of its one-hop neighbours as multipoint relays. The MPRs are chosen so that all two-hop neighbours of a node will be reached if all its MPRs retransmit a message. To select the MPRs, a node requires updated information about its two-hop neighbourhood.

Control traffic in OLSR is mainly exchanged through two different types of messages: hello and Topology Control (TC) messages. Hello messages are exchanged periodically among neighbour nodes in order to detect links to neighbours and to signal MPR selection. In addition to giving information about neighbour nodes, periodic exchange of hello messages also allows each node to maintain information describing the links between neighbour nodes and nodes two hops away. This information is recorded in a node's 2-hop neighbour set and is explicitly utilized to do the MPR selection.

TC messages are periodically flooded to the entire network in order to send link state (topological) information to all nodes. Only nodes that have been selected as an MPR node generate (and relay) TC messages.

3 Routing Solution

In this study, all nodes consist of an L3 router and one or two waveforms. A schematic picture of a node is shown in Figure 3.1. It shows a network layer consisting of an L3 router with two underlying waveforms. The L3 router is responsible for routing between the waveforms and in this report three different OLSR-based routing-daemon solutions are presented. Normally, the routing is done only at L3. However, the radio systems may have a built-in router also at L2. Advantages and disadvantages of having radio systems with built-in routers are described in [5].

In the first part of this chapter, the waveform types are presented. The second part describes modified OLSR daemon used by the L3 router and in the last, the neighbourhood discovery (NHD) protocol in the SCB-based waveform is described.

3.1 Waveform Types

In this report two different type of waveforms are considered. The first waveform, denoted TDMA, has an L2 router using an OLSR-based routing daemon on top of a MAC layer using TDMA. The second waveform, denoted SCB, is based on a MAC layer using SCB and has no L2 router. To make the waveforms more similar from an L3 router perspective, a neighbourhood discovery (NHD) protocol is added to the MAC layer for the second waveform, enabling it to support the L3 router with topology information. SCB with neighbourhood discovery is described further in Section 3.3.

3.2 OLSR Modifications for L3

In [1], two modified versions of OLSR was presented, muted OLSR (OLSR-M) and cross-layer OLSR (OLSR-XL), both with aim to reduce the MPR-flooding

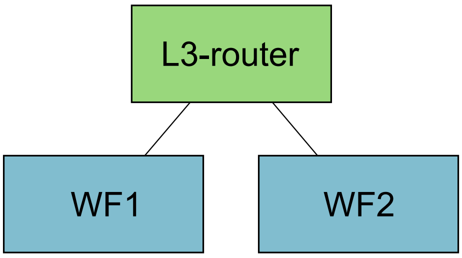


Figure 3.1: Schematic design of a radio node with an L3 router and two underlying waveforms.

cost for control and user traffic. The muted OLSR entails that an MPR never retransmits a packet to the receiving interface. OLSR-XL also uses muted functionality, but with additional cross-layer modifications.

The two main additions to OLSR introduced in OLSR-XL is detection of links at L3 solely on information from L2 and reactive hello messages. The reactive hello messages are sent when the topology changes but with a limitation in how often they are sent by a parameter specifying the minimum interval. More information about the previous modifications are to be found in Appendix A. The mentioned settings are for comparison included in this report, denoted OLSR-XL1.

In this extended study an additional L3-router daemon solution is implemented, named OLSR-XL2. The OLSR-XL2 uses all changes from OLSR-XL1 but with some new insertions, where the main contribution is compression of L3 addresses. In military tactical networks, predefined address plans are often used. In such plans the address range used for a network segment is often relatively small, a property that can be used to reduce the overhead cost.

Instead of sending full addresses of 32 bits of all included neighbours with every hello and TC messages, as in Figure 3.2a, all nodes with subsequent addresses are represented by a field in a vector. For every sequence, the full address of the first node, the number of nodes and a vector, is sent, Figure 3.2b. This vector has different numbers of bits dedicated to each neighbour depending of the message type. For TC messages it only needs one bit indicating which neighbours that have selected it as an MPR. For hello messages, four bits are needed as the link code is included in the vector and it contains twelve cases (four link types and three neighbour types as specified by the RFC).

This method may have potential to compress the addresses noticeable for subsequent nodes, as in the example in Figure 3.2 where twelve sequent nodes can be send within the same space as three full node addresses. When the used addresses are more spread out, as in the interconnecting waveform, the gain is less.

In the standard OLSR protocol, hello and TC messages are generated with a predefined interval of a few seconds. For OLSR-XL2, these intervals are defined to be very long in order to reduce the overhead, and both hello messages and TC messages are almost exclusively sent reactively, triggered by link and topology changes in the network.

TC messages are already sent in a reactive manner in the OLSR standard when changes in the MPR selection set has occurred. However, with net merges or nodes joining a network, these new nodes will not receive any TC message updates from nodes further away in the network than the 2-hop neighbourhood, making new nodes unable to route data to the entire network. In OLSR-XL2,

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      First node address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                     Second node address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                              ...                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

(a) Typical representation of addresses in OLSR.

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                      First node address                       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Number of nodes|       |       |       |       |       |       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|       |       |       |       |       |       |       |  ...
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

(b) Our compression where four bits are devoted to each address after the first header.

Figure 3.2: How L3 addresses are sent within the message.

this is solved by triggering extra reactive TC messages for these situations. This is done by investigating all received TC messages, looking for entries including node addresses previously unknown to the node. If a previously unknown node is detected, TC message generation is triggered. Since this is only a problem that arise in net merge situations with networks with more than two hops, a specific simulation scenario was set up for the purpose of demonstrating this feature. The results from this can be found in Appendix B.

New for OLSR-XL2 is also the the ability to send additional hello and TC messages. With this enabled, a number of additional hello or TC messages will be sent by the source node within a shorter interval after that the node has been triggered by a topology change to reactively send such a message. This will increase the robustness of the protocol by ensuring that a single packet loss does not cause too much problem, as the time until next message is sent otherwise may be very long if no further topology changes occur.

The distinctions of the two presented L3-router solutions (OLSR-XL1 and OLSR-XL2), as well as the standard OLSR (OLSR-STD), are summarized in Table 3.1. The parameters used for the hello and TC message intervals and number of additional transmissions are listed in Table 3.2.

Table 3.1: Distinctions of the three L3-router types.

Description	OLSR-STD	OLSR-XL1	OLSR-XL2
No retransmission on L2 (mute)	no	yes	yes
Cross-layer information on L2	no	yes	yes
Reactive hello message generator	no	yes	yes
Message compression	no	no	yes
Additional hello and TC messages	no	no	yes
Extra reactive TC messages enabled	no	no	yes

Table 3.2: OLSR hello and TC message parameters.

Description	OLSR-STD	OLSR-XL1	OLSR-XL2
Hello message interval (s)	2	1200	1200
TC message interval (s)	5	5	1200
Hello message minimum interval (s)	not used	2	2
TC message minimum interval (s)	2	2	2
Number of additional hello messages	0	0	1
Number of additional TC messages	0	0	1
Additional hello message interval (s)	not used	not used	12
Additional TC message interval (s)	not used	not used	12

3.3 SCB with Neighbourhood Discovery

To make the analysed waveform types more similar from an L3-router perspective a neighbourhood-discovery (NHD) protocol is added to the SCB-based waveform. In its original form the used SCB lacks routing functionality, so the neighbourhood-discovery algorithm creates an image of the network topology. It uses methods similar the ones used by OLSR to detect if a link is symmetric, asymmetric or lost between nodes in the SCB network. Dedicated topology control messages announce the node's one-hop neighbours. If a receiving node has its own node number announced in n subsequent messages it changes the neighbour's status to symmetric. Due to the robustness of SCB, a single missing message indicates something is wrong and therefore the neighbour's status is set to *lost*.

NHD uses the same packet compression as described in Section 3.2, but here L2 messages are compressed instead. The vector has two bits for each node because it uses a link code with symmetric, asymmetric and lost-link options. With the current application one bit would be sufficient since a received message in which the receiving node's status is asymmetric indicates that the link actually is symmetric. This has however not been implemented, so two bits are used.

4 Simulation Model and Setup

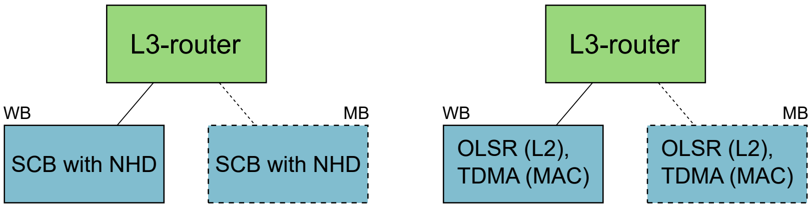
All nodes in this setup are using either one or two waveforms. Nodes within the same company are connected with a wideband (WB) waveform with a bandwidth of 1 MHz. Gateway nodes, which are connecting the companies, has also a mediumband (MB) waveform of 250 kHz. The waveforms uses frequency bands at 300 MHz and 50 MHz respectively, and therefore has different path loss. Within a simulation, the WB and MB waveforms are always of the same type, as seen in Figure 4.1b and 4.1a.

Six nodes in each company are equipped with the MB waveform interface: the company commander, the deputy company commander and the four platoon leaders. In the first setup both waveforms ran SCB integrated with NHD. In the second setup both waveforms ran OLSR on L2 and a TDMA protocol on the MAC layer. An L3 layer with OLSR connected the two waveforms. Three different L3 solutions based on OLSR were evaluated by simulations. The distinctions between the simulations are summarized in Table 4.1.

All the simulations were performed using Aquarius, an in-house radio network simulator. The simulator is written in C++ and models the system at packet level. Scenario description, simulation model and performance metrics are described further below. The simulation models for the data link and physical layer are the same as in [1]. The description of these layers is in Appendix C.

4.1 Scenario Description

The same scenario as in [1] was used. It consisted of a part of the troop deployment vignette of a mechanized battalion in the Anglova scenario [6]. A subset of the battalion was used, consisting of the nodes forming two mechanized infantry companies and two tank companies. Furthermore, focus was on the phase from scenario time 5500 seconds to 6501 seconds (Figure 4.2).



(a) SCB (b) TDMA

Figure 4.1: The two waveform configurations used, where the dashed MB waveform only is present in a subset of the nodes. The L3 router uses any of the OLSR modifications from Section 3.2.

Table 4.1: Distinctions of the simulations.

Description	Alternative
Number of nodes	24, 48, 72, 96
Traffic type	multicast, unicast
L3-router type	OLSR-STD, OLSR-XL1, OLSR-XL2
Waveform type	SCB, TDMA
Waveform bandwidth	WB, MB

The positions of each platoon at 6501 seconds are also shown in 4.2. On average, the nodes moved with a velocity of 15 km/h. In the evaluation, networks consisting of one, two, three, or all four companies were considered, i.e. the different total network sizes were 24, 48, 72 or 96 nodes. The companies were added from the right in Figure 4.2: company 1 was added first then 3, 4 and lastly company 2.

To model the large-scale behaviour of the radio channel in the scenario, a UTD-model [7] in the propagation library DetVag-90® was used [8]. The antenna heights were set to 3 meters for all nodes and a digital terrain database was used.

4.2 Application Layer

Both user and overhead traffic was sent in the networks. The user traffic was modelled as unicast or broadcast transmissions of packets. The unicast traffic was sent between randomly selected nodes pairs, and the broadcast traffic was sent from randomly selected nodes to all the nodes in the network. All packets were of equal size and were generated according to a Poisson process with a mean arrival rate of 1 packet per node per second. The traffic load in the network was sufficiently low to prevent packet queues from building up in the nodes. A sent packet may however not reach an intended receiving node if the link to that node disappeared, resulting in reduced packet delivery ratio.

4.3 Network Layer

In the used router setup, L2 appears as a network interface at L3. From the L2 perspective, L3 appears as an extra network protocol. When a packet is passed from L3 to L2, the next hop address set by L3 is used as the destination address in L2. Furthermore, if the destination address is a broadcast address, the destination address is remapped to *all hosts* multicast group (the IP address for all hosts on the same network segment). Hence, from the L3 perspective,

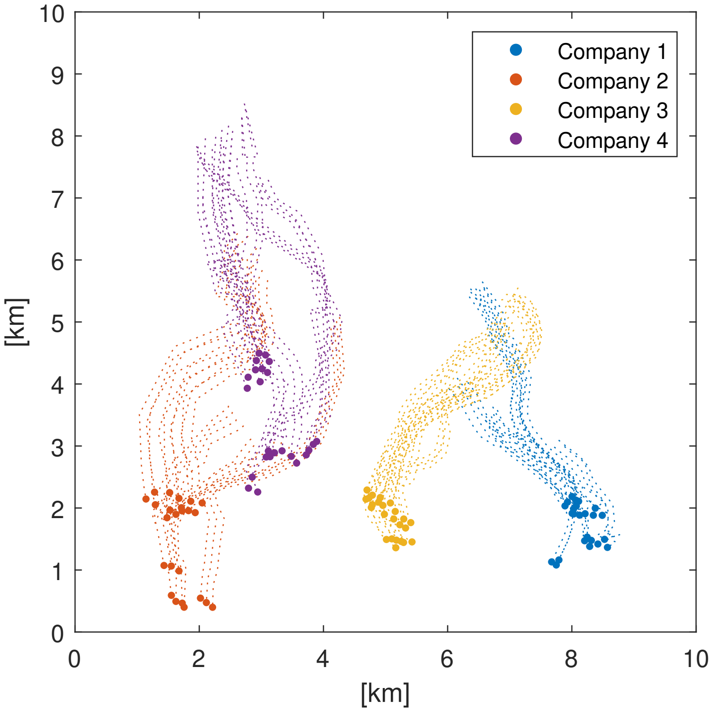


Figure 4.2: The trajectories for the vehicles from Anglova Vignette 2 that were used in the simulations.

L2 will appear as a one-hop network.

In the simulations, both L2 and L3 utilized OLSR. The L3 daemons ran on the designated UDP port while the L2 daemons ran as a network protocol. The OLSR algorithm normally uses Multiple Interface Declaration (MID) messages to distribute interface information to the network [4]. To reduce the OLSR control traffic, the interface information spread by the MID messages was assumed to be preconfigured in the nodes and thus, it was turned off here.

4.4 Performance Metrics

Performance was measured in terms of Packet Delivery Ratio (PDR) in the network, average number of transmissions for a data packet, and overhead traffic sent by OLSR. The overhead was measured both as the percentage of the network load caused by the the L3 router and as the average signalling overhead of the hello and TC messages passed down from L3 to L2. Both overhead metrics are measured per network. For WB waveforms the presented result is an average over the used networks. Performance was measured in terms of Packet Delivery Ratio (PDR) in the network, average number of transmissions for a data packet, and overhead traffic sent by OLSR. The overhead was measured both as the percentage of the network load caused by the the L3 router and as the average signalling overhead of the hello and TC messages passed down from L3 to L2. Both overhead metrics are measured per network. For WB waveforms the presented result is an average of the existing nodes.

The focus of this study was to analyse design requirements for an L3-routing solution. However, if the control traffic of OLSR overloaded the network, the usefulness of the simulation would be limited. Hence, the size of the OLSR packets seen by the lower layers are set to zero so that they would never cause overload. Note that this did not affect the measured overhead traffic sent by OLSR, which was based on the real packet sizes. The overhead created by headers on layers below OLSR, primarily IP and UDP, is not negligible, but can be hard to estimate as they can be reduced by the radios. Therefore, the OLSR headers and payload, in terms of bits/s, are included in the overhead but additional headers added on transport layer or below are not counted.

5 Results

This chapter presents the results from simulations with the scenario and system setup described in Chapter 4.

5.1 Packet Delivery Ratio

For the scenarios studied in this report, the networks formed by the MB respectively WB waveforms are always connected. Hence, a packet delivery ratio of one can be achieved by well functioning systems, while a PDR below one indicates that the topology changes are challenging for the waveforms or for the L3-router daemon.

Figure 5.1 and 5.2 shows the PDR for unicast and multicast traffic respectively for the network consisting of 48 nodes. Six different curves are shown which combines the two types of waveforms and the three L3-router types. As can be seen, the PDR varies over time for the TDMA based waveforms while SCB based waveforms have a constant value of 1. Since the L3 routers are the same, the results show the superiority of SCB regarding robustness due to cooperative communication and high network diversity.

For TDMA based waveforms (shown as red, orange and yellow i Figure 5.1 and 5.2) the PDR drops in the later half of the scenario due to high mobility and possibly also due to longer routes. As an effect of topology changes caused by the mobility in this scenario, all OLSR/TDMA solutions had difficulties updating routing information in a timely manner. The overall higher PDR values for multicast traffic is most likely an effect of the generally higher robustness of MPR-flooding [9, 10, 11].

For the TDMA based waveforms, OLSR-XL1 and OLSR-XL2 have slightly lower PDR than the OLSR-STD solution. Note that the L3 router is parametrized to match the L2 router of the WB waveform, while the L2 router for the MB waveform has a slower link detection rate, see Appendix C.1. As an effect of this, the reactive OLSR solutions have a slower detection of topology changes. This can also explain the deeper PDR drops in challenging situations.

In Figure 5.3 and 5.4, the PDR is shown as an average over time for the four different network sizes and our six evaluated combinations, for unicast and multicast traffic respectively. Note here the difference in scale on the y-axis compared to previous PDR figures. Generally, the PDR decrease with increasing network size, an effect of longer routes and an increasing number of MPR nodes necessary to reach the destinations as the network size increase.

The lower PDR values for TDMA with OLSR-XL1 (shown as orange bars in Figure 5.3 and 5.4), most evident in the biggest network, are most likely an

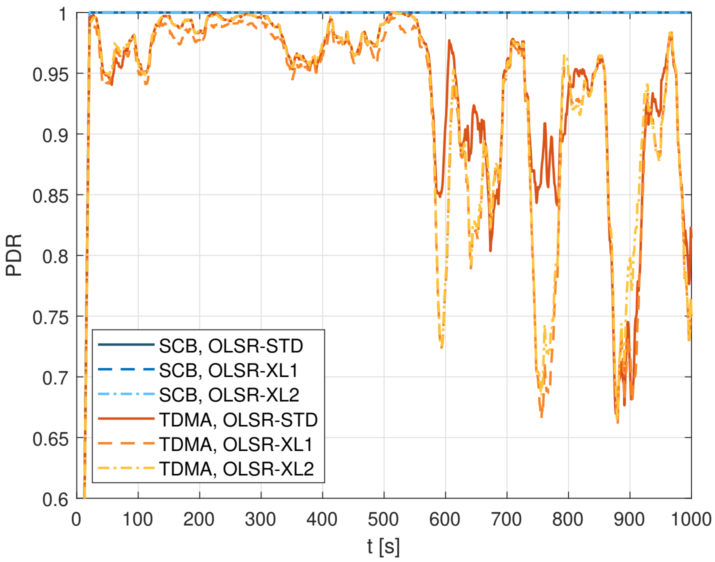


Figure 5.1: For unicast traffic: PDR over time for the network consisting of 48 nodes.

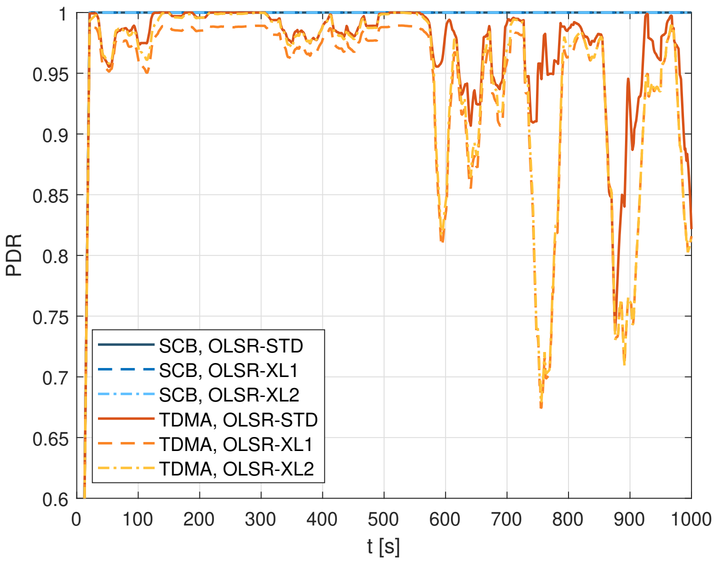


Figure 5.2: For multicast traffic: PDR over time for the network consisting of 48 nodes.

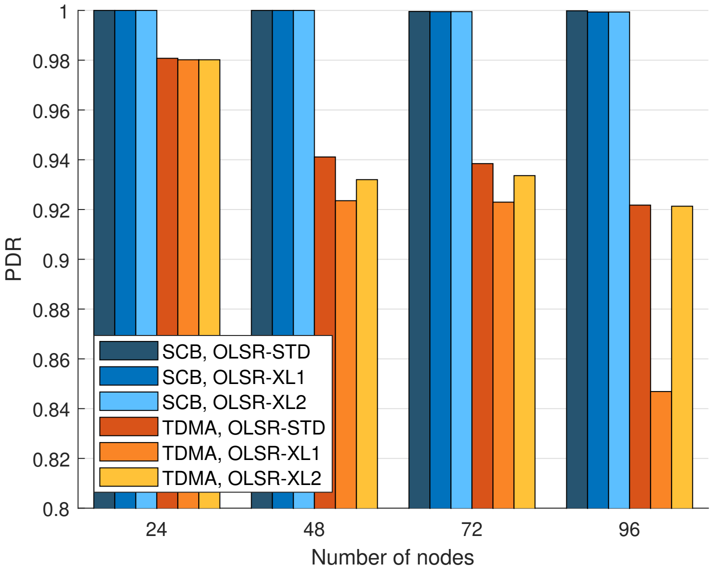


Figure 5.3: For unicast traffic: PDR of different network sizes.

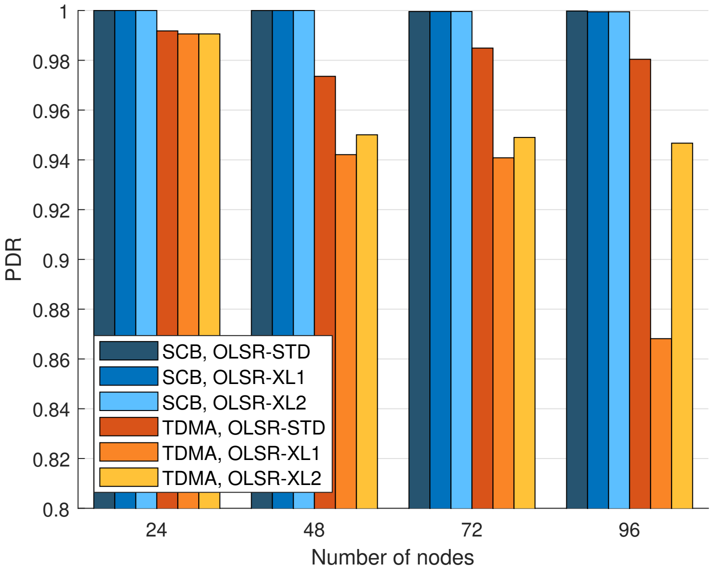


Figure 5.4: For multicast traffic: PDR of different network sizes.

effect of a lost hello message. Since OLSR-XL1 uses reactive hello messages, the time until a new hello message is sent may be long if there are few later topology changes in the network. Hence, the effect of a lost hello message can be significant for the OLSR-XL1 solution. This is solved by introducing the additional hello messages in OLSR-XL2.

5.2 Transmissions per Data Packet

Figure 5.5 to 5.8 show the average number of transmissions per data packets summed over the available networks for unicast and multicast traffic in combination with different waveforms (MB and WB). The transmissions are separated in MB and WB and therefore the total number of transmissions are obtain by adding the MB and WB transmissions. Note the difference in scale on the y-axis between the figures of multicast and unicast traffic.

Notable here is that the figures show the number of data packets sent down to the MAC layer, and hence it does not show the retransmissions at lower layers. For TDMA, the number of transmission at the lower layer is dependent on the route length (for unicast) or the number of relaying MPR nodes (for multicast). For the SCB solution used here, the relay cost is a part of the SCB protocol. Hence, the cost is constant, here with the CB slots four times (equal to the reuse distance) larger than the TDMA slots. This can be interpreted as a four times lower data rate for SCB. It can however be solved by introducing an adaptive reuse distance, which is made possible by the neighbourhood discovery algorithm. If the source node has a full picture of the routing table in the network, the reused distance can be set adaptive as the maximum number of hops.

The networks with just 24 nodes did not need the MB waveform since it only involved one company which is connected with the WB waveform. Therefore the MB unicast figure starts at zero for the smallest network. For MB multicast the number of transmissions is slightly above zero due to the time required to discover the topology of the network at startup. For WB, the graphs starts at or above one since at least one transmission is needed for the packet to reach its destination.

For unicast traffic (Figure 5.5 and 5.6), the graphs describing the three L3 OLSR solutions with SCB based waveforms are on top of each other. As long as the nodes are connected, the SCB based waveforms are able to find a route between the nodes. Therefore the lower layers looks to behave as a one-hop network for the L3 router.

OLSR-XL1 with TDMA has a deviating point for the largest network size in Figure 5.5 and 5.6. The reason for the lower number of transmission is in this case an effect of the loss of routes, resulting in packets only being sent part of the way to the destination.

For multicast traffic (Figure 5.7 and 5.8) there is a significant reduction in the number of transmission between the cross-layer router types and the standard OLSR. The main reason is the muted functionality which prevents retransmission on the receiving waveform.

5.3 Overhead

The overhead for the different waveforms and the OLSR modifications is shown in Figure 5.9 and 5.10. Only the overhead generated by the L3-routing daemon is included in these figures whereas the L2-routing daemon overhead is discarded, as only the effects of the modifications on L3 were of interest for this investigation. In difference to Figure 5.5-5.8, these figures also include retransmission of the hello and TC messages generated by the L2 router.

Figure 5.9 and 5.10 show the percentage of the network load caused by OLSR L3, for the six configurations. Note the difference in scale between the figures. This figures are weighed with the data rate which is approximately four times lower for SCB than for TDMA, as SCB always needs a full CB slot for each transmission. As can be seen in Figure 5.10, using the SCB based waveform on MB with OLSR-STD causes an overhead of approximately half the channel capacity for our largest network. This is however notably lowered by the cross-layer solutions. An overhead below 10 % can be seen as manageable.

Figure 5.11 and 5.12 shows the average signalling overhead of the hello and TC messages passed from L3 down to L2 in the 96 node network. For readability, the values can also be found in Table 5.1. As expected OLSR-STD, which does not use the muted functionality, has higher TC message overhead than the cross layer versions. The TC message overhead is decreased further due to the message compression and the use of long update intervals together with the use of extra reactive TC messages in OLSR-XL2. The hello message overhead shows an even bigger decrease due to the introduction of reactive hello messages. The decrease of hello message overhead between OLSR-XL1 and OLSR-XL2 is mostly due to message compression.

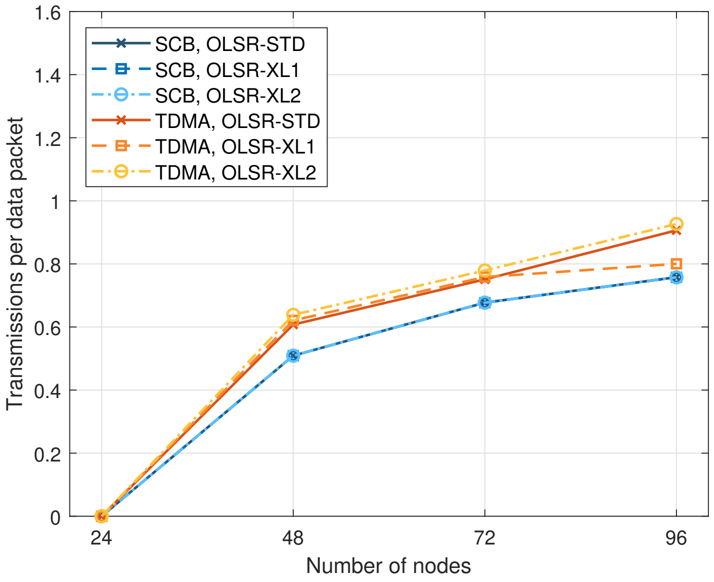


Figure 5.5: For unicast traffic and MB waveform: Number of transmissions per data packet for different network sizes.

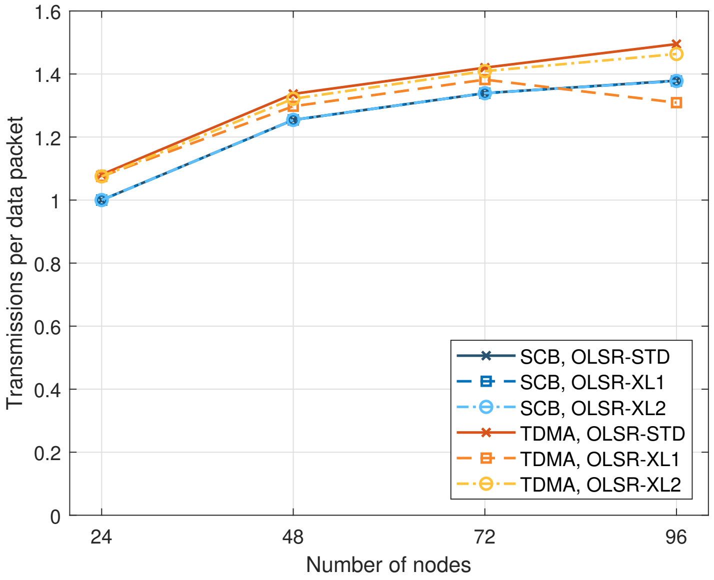


Figure 5.6: For unicast traffic and WB waveform: Number of transmissions per data packet for different network sizes.

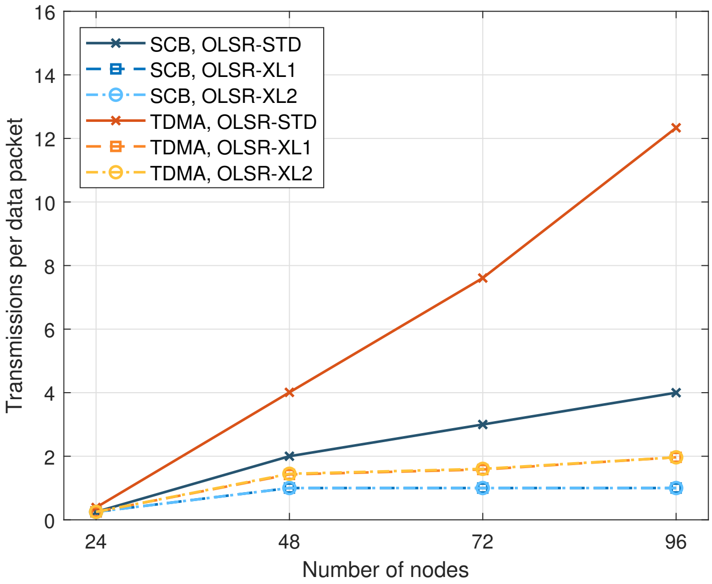


Figure 5.7: For multicast traffic and MB waveform: Number of transmissions per data packet for different network sizes.

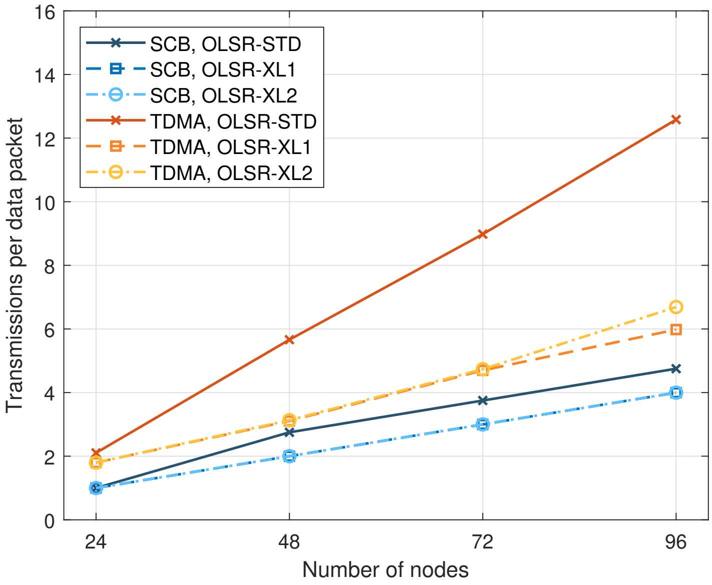


Figure 5.8: For multicast traffic and WB waveform: Number of transmissions per data packet for different network sizes.

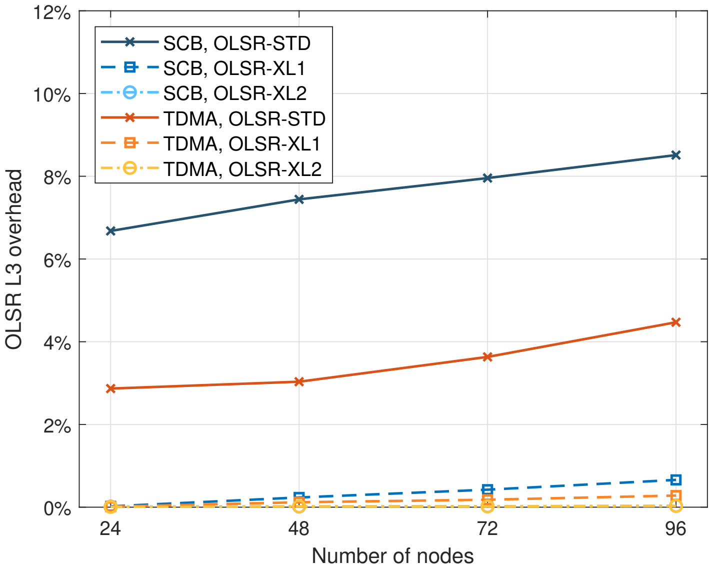


Figure 5.9: For WB: Percentage of available bit rate used by overhead generated on L3 for different network sizes.

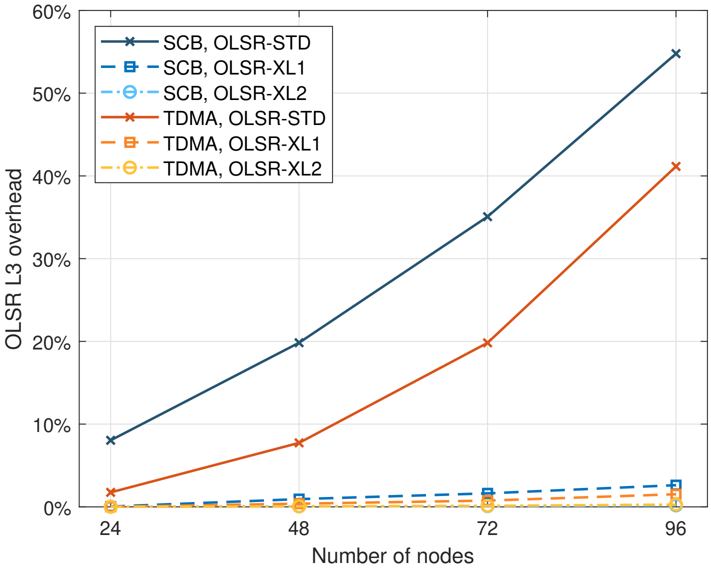


Figure 5.10: For MB: Percentage of available bit rate used by overhead generated on L3 for different network sizes.

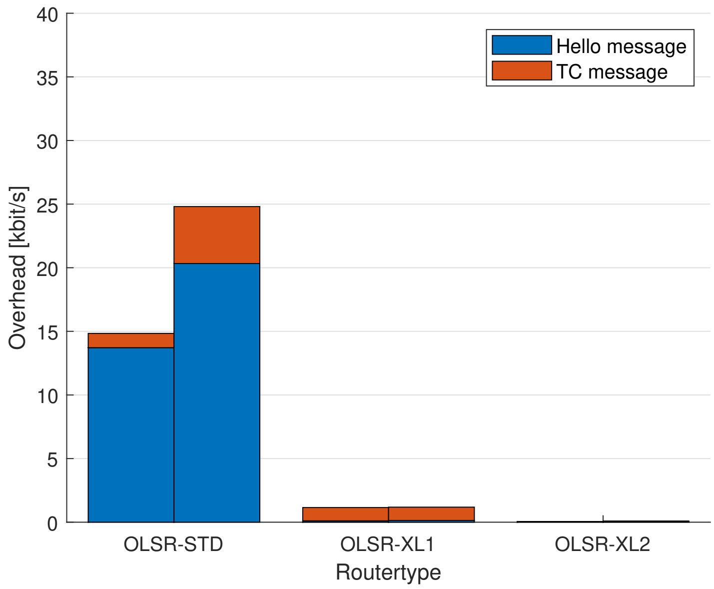


Figure 5.11: For the SCB waveform: The amount of signalling overhead passed from L3 to L2 for the different router types and the network consisting of 96 nodes. For each router type, the bars to the left are WB and the ones to the right MB.

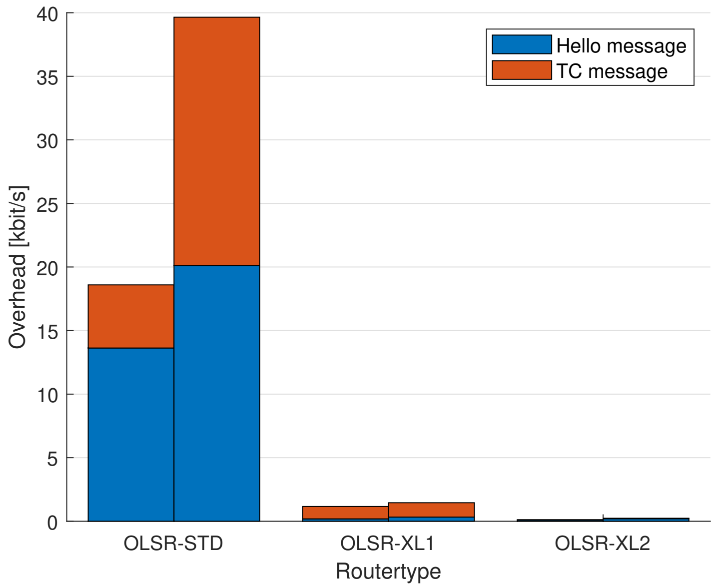


Figure 5.12: For the TDMA waveform: The amount of signalling overhead passed from L3 to L2 for the different router types and the network consisting of 96 nodes. For each router type, the bars to the left are WB and the ones to the right MB.

Table 5.1: Signalling overhead passed from L3 to L2 in bit/s for the 96 node network. Values rounded to integers.

Description	Hello message		TC message		Total	
	WB	MB	WB	MB	WB	MB
SCB						
OLSR-STD	13715	20331	1123	4475	14838	24806
OLSR-XL1	107	137	1045	1047	1152	1184
OLSR-XL2	49	73	4	5	53	79
TDMA						
OLSR-STD	13628	20115	4965	19531	18593	39646
OLSR-XL1	187	330	973	1126	1160	1456
OLSR-XL2	97	200	22	37	120	237

6 Conclusions

In this report, a heterogeneous network was studied, consisting of WB company networks and an interconnecting MB network. Two types of waveforms were analysed. The first waveform was based on SCB. In order for SCB to be able to deliver topology information to the layer 3 router, a neighbourhood discovery procedure was developed and integrated with SCB. The second waveform was based on OLSR at layer 2 together with TDMA as MAC protocol.

Different solutions to interconnect the networks based on OLSR routing at layer 3 were investigated. Standard OLSR and two modified versions, OLSR-XL1 and OLSR-XL2, were analysed. The results showed that overhead was reduced with the modified OLSR versions. In particular, the following modifications are important: (1) do not retransmit a packet on the receiving interface, (2) deliver network topology information to layer 3, (3) establish support for reactive control messages, (4) use packet compression for the control traffic. All these modifications are exploited by OLSR-XL2. There is some room for further improvements, but OLSR-XL2 offers a reasonable solution. The routing overhead is low and a high PDR can be maintained. In general, the setup with waveforms based on SCB worked better than the setup with waveforms based on OLSR and TDMA.

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A OLSR Modifications

The following modifications denoted as OLSR-XL were made in [1], compared to the specification in RFC 3626 [4]. These changes are default settings in both OLSR-XL1 and OLSR-XL2 in this report.

- The detection of links at L3 is only based on information from L2.
    - When links and associated neighbours are inserted in the OLSR database, the expire time parameter is set to infinity.
    - Links and associated neighbours at L3 are removed immediately when the corresponding route at L2 is detected as broken.
- A node only sends a hello message when L3 detects a link change or when the MPR selection changes.
- The minimum time between two hello messages is never less than the *minimum hello interval* parameter, which is set to two seconds in the present setup.
- When a hello message is received, only MPR selectors and two-hop neighbours are updated according to the information in the message. In both cases, the expire time parameter is set to infinity. Two-hop neighbours and MPR selectors are removed from the database if they are missing in the hello message or if the associated neighbour is removed.
- If the MPR set is changed, additional TC messages will be sent. The minimum time between two TC messages is never less than the parameter *minimum TC interval*, which is set to two seconds in the present setup.

B Additional Simulation Results

This appendix chapter describes the results from a net merge scenario simulation created to test the OLSR-XL2 feature with extra reactive TC messages.

When using very long TC intervals in order to reduce the overhead, the routing protocol must rely on all necessary TC messages being generated reactively, triggered by link and topology changes in the network. TC messages are already sent in a reactive manner in the OLSR standard regarding detection of changes in the MPR selector set. However, with net merges or nodes joining a network, the new nodes will not receive any TC message updates from nodes further away in the network than the 2-hop neighbourhood, since those nodes further away may not have any changes in their 2-hop neighbourhood and MPR selector sets. This would make the new nodes unable to route data to the entire network until either the regular TC interval is reached or another topology change occur in those other parts of the network. Here, we solve this problem by triggering extra reactive TC messages for these situations.

This is done by investigating all received TC messages, looking for entries including node addresses previously unknown to the recipient node. Nodes at net merge or new joining nodes will need to select MPR:s, therefore their addresses will be added to the TC messages by their respective MPR nodes, and further relayed into the entire network, reaching all nodes to which they are connected, yet unknown. An unknown node here meaning a node that is not currently in any of the OLSR database sets of neighbours and topology. Therefore, if a previously unknown node is detected by an MPR node when investigating a received TC message from some other node in the network, TC message generation in this node is triggered.

Since this is only a problem that arise in net merge situations with networks with more than two hops, a specific simulation scenario was set up for the purpose of testing this feature. The scenario consists of 15 nodes grouped in 3 networks with 5 nodes, each group connected in a chain over the WB waveform. Each of the end nodes in these chains (node 1, 5, 6, 10, 11 and 15) also have an interface to a MB waveform network. The network topology at the start of the scenario is illustrated in Figure B.1. Red lines represent links in the WB networks. The blue line represent the link over the MB waveform net. After 30 minutes, a link between node 5 and 6 will appear over the MB waveform net, creating a net merge in the scenario. The connected state will then remain unchanged until the end of the scenario, which is 60 minutes long in total.

For this scenario, unicast traffic is sent from node 1 and 15. To measure at what time the nodes far off in this network will have a working unicast route, received packets are measured at application level in each node over the time of

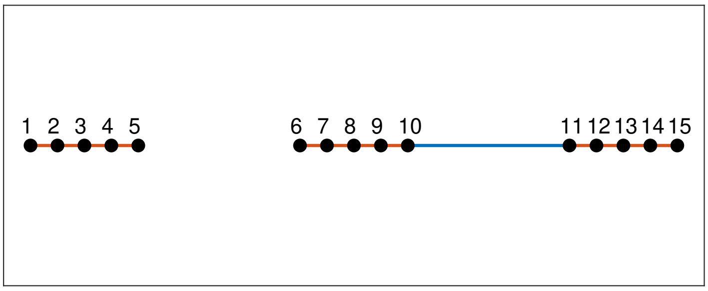

Figure B.1: Network topology at the start of the simulation. Red lines represent links in the WB networks. The blue line represent the link over the MB waveform net. After 30 minutes node 5 and 6 will also have a link over the MB waveform net.

the entire scenario. Apart from varying the TC interval and the ability to send extra reactive TC messages, the simulations otherwise use the same parameter settings as described for OLSR-XL2 in this report. To show what happens at net merge using these different TC message settings, results from simulation using the default OLSR standard TC interval (5 seconds) are compared with those using a larger interval, with or without enabling the feature with extra reactive TC message generation.

The results from the simulations show that when increasing the TC interval from 5 seconds (default) to 12 minutes, the data sent from node 1 to node 15 is not received until 6 minutes later. This is seen in Figure B.2 where the data received using the 5 seconds default interval is shown in red, and the data received using the long 12 minute interval is shown in blue. The reason for the delay of 6 minutes is because the event at 30 minutes is appearing just in the middle of a TC interval in this scenario. Since nothing happens after the net is established a few seconds in to the simulation, TC messages will be sent after 12 minutes, 24 minutes, 36 minutes, and so on. In general the delay from a TC message update after an event at a random time will be between 0 and TC interval, so in mean half the TC interval. Comparing Figure B.2 with Figure B.3 shows that the data sent from node 1 to node 15 is received just as quickly when extra reactive TC messages are enabled and using an otherwise long TC interval of 12 minutes (the received data shown in green in Figure B.3), as when using the default TC interval of 5 seconds (the received data shown in red in Figure B.2). The overhead is however much lower when using the extra reactive TC messages together with a long TC interval, compared to the comparably short default TC interval.

For the default OLSR protocol setup with a short TC interval, the overhead is mostly determined by the interval. For a long TC interval, the overhead will instead depend on the topology changes (and how many additional messages that are set to be sent, see Chapter 3.2). In this scenario, node 10 and 11 are the MPR nodes affected by this extra reactive TC message trigger. Here, the extra amount of TC messages generated for this single link appearance event is two TC messages (plus the additional messages configured to be sent, if any), which then also will be forwarded/retransmitted as all TC messages are.

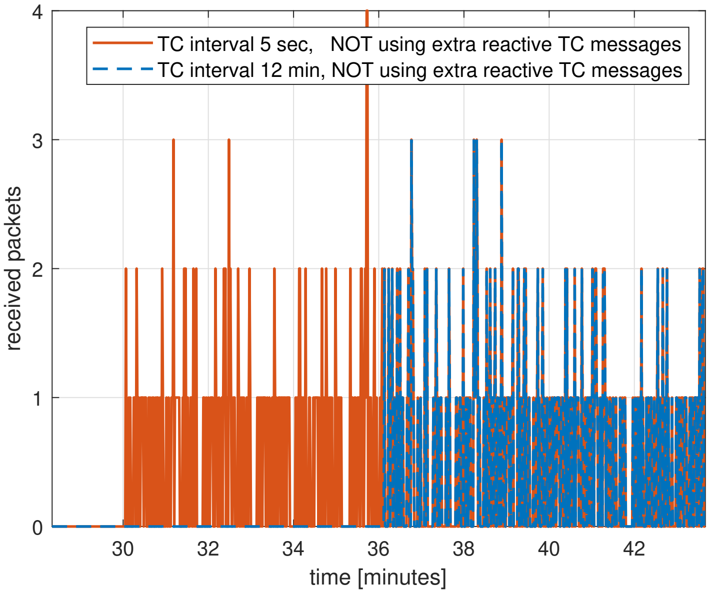

Figure B.2: Received packets by node 15 over time, comparing the default TC interval with a long TC interval without extra reactive TC messages.

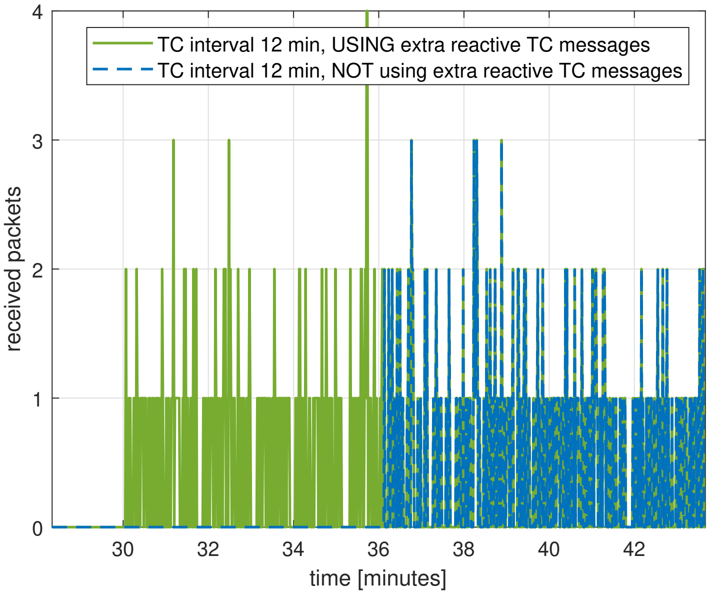

Figure B.3: Received packets by node 15 over time, comparing when extra reactive TC messages are enabled or not, using the same (long) TC interval.

C Waveform Configurations

The parameter settings for the used OLSR/TDMA based waveforms and the SCB based waveforms are presented below.

C.1 L2 Router Daemon

The TDMA based waveforms has an L2 router using an OLSR based routing daemon. To increase the robustness of OLSR, a signal-to-noise ratio (SNR) method is used to decide if a link is reliable or not, see [12]. Hence the L2 routing daemon is assumed to have access to SNR estimates from the lower/ physical layer. No extra SNR margin is used by the daemon, i.e. if packet can be received by the physical layer the link is considered reliable. The parameter settings for the daemon are presented in Table C.1.

C.2 TDMA

The TDMA based waveforms used a static TDMA MAC protocol. The protocol divides the time into time slots, which are grouped into repeating frames. Each node in the network has a time slot in each frame. The parameters describing the time-slot structure for the two waveforms are presented in Table C.2.

C.3 SCB

The parameters describing the time-slot structure for SCB are presented in Table C.3. For MB waveform, the data rate varies with the number of nodes hence the data rate for 24, 48, 72 and 96 nodes are presented.

C.4 Physical Layer

The physical layer was modelled at packet level in the simulator. To increase the robustness, the system used frequency hopping. Thus, each packet was

Table C.1: OLSR parameters for the L2-router daemon.

Description	Value		Unit
	WB	MB	
Hello interval	2	4	s
TC interval	5	10	s

Table C.2: MAC layer parameters for the TDMA waveform. Values rounded to one decimal.

Description	Value		Unit
	WB	MB	
Time slot length	2.7	5.1	ms
Frequency hops per time slot	3	3	-
Frequency hopping tuning time	100	100	μs
Time slot guard time	100	100	μs
User data rate	740.7	194.7	kbit/s

Table C.3: MAC layer parameters for the SCB waveform. Values rounded to one decimal.

Description	Value		Unit
	WB	MB	
CB slot length	10.8	20.5	ms
Time slot length	2.7	5.1	ms
Frequency hops per time slot	3	3	-
Frequency hopping tuning time	100	100	μs
Time slot guard time	100	100	μs
User data rate	176.7	41.1, 44.1, 45.2, 45.7	kbit/s

divided into h packet segments that were transmitted on consecutive frequency hops. Slow frequency hopping was used, so several symbols were transmitted on each hop. All packets were coded over all h hops. Furthermore, it was assumed that the diversity obtained by frequency selective fading and frequency hopping was sufficient to ignore the effects of small-scale fading [9].

A packet was successfully received if the total channel capacity average over the entire packet length, T_p , exceeded the threshold C_γ, as described in

$$\frac{1}{T_\text{p}} \sum_{i=1}^{M} C_i \Delta t_i > C_\gamma \tag{C.1}$$

where Δt_i is the time duration over which the channel capacity C_i is constant and M is the number of these time intervals. The channel capacity C_i was calculated as

$$C_i = \min\left(C_\text{max}, \log_2\left(1 + \frac{S_i/L_\text{imp}}{W_\text{c}N + I_i}\right)\right) \tag{C.2}$$

where S_i is the aggregated received signal power on the intended communication channel, L_imp is the implementation loss, W_c is the bandwidth of the communication channel, N is the noise spectral density and I_i is the interference on the intended communication channel. There is also a limitation on the

Table C.4: Physical layer parameters.

Parameter	Description	Value		Unit
		WB	MB	
P	Output power	47	47	dBm
L_{imp}	Implementation loss	10	10	dB
W_{c}	Channel bandwidth	1000	250	kHz
f_{c}	Center frequency	300	50	MHz
F	Noise figure	10	16	dB
R	Link data rate	1000	250	kbit/s
C_{γ}	Channel capacity threshold	1	1	bit/s/Hz
$C_{\max}$	Max channel capacity	1.55	1.55	bit/s/Hz
-	Preamble length	128	256	μs
-	SNR threshold preamble synchronization	0	0	dB

channel capacity, $C_{\max}$, to prevent the capacity from exceeding the maximum possible capacity of the specified modulation and coding scheme.

The parameter settings for the physical layer of the two waveforms are presented in Table C.4.

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