Ethernet in Automotive Networks

Design and evaluation of rate constrained
Ethernet stack transporting J1939 messages

E R I K M A T Z O L

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E R I K M A T Z O L S

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Abstract

Ethernet as a backbone in automotive networks would to a great extent reduce the current bus load on the bandwidth limited CAN-bus. In the future more bandwidth is needed and new features require more bandwidth.

In this report, three real-time Ethernet protocols are analyzed (AFDX, TTEthernet and Ethernet AVB). As a result from the investigation a software stack is designed and implemented using the AFDX protocol.

The prototype uses a concept called virtual links to partition the available bandwidth. A periodic scheduler limits the bandwidth based on two parameters set for each virtual link. The bandwidth allocation is statically defined for each virtual link. As a result the buffer sizes in the Ethernet switch can be decided and as a consequence an upper bound on the transmission latencies.

The prototype is tested with sending and receiving simulated J1939 messages in two experiments. The first experiment uses accumulation of message frequencies to parameterize the virtual links. The second experiment encapsulates multiple messages in a single Ethernet packet. The primary results from the experiments were that encapsulation of multiple messages in a single Ethernet packet is more efficient.

An advantage with the protocol is that it is possible to use with current smart Ethernet switches. An idea how the solution gradually could be introduced has been identified as future work. However, it is necessary to further investigate the electrical layer, electromagnetic compatibility and cabling. The conclusion for the degree project is that the protocol is suitable to use in future Ethernet applications.

Ethernet i fordonsnätverk

Design och evaluering av flödesbegränsad Ethernet-stack vid transport av J1939-meddelanden

Sammanfattning

Ethernet som en stomme i fordonsnätverk skulle till stor del minska den nuvarande busslasten på den begränsade CAN-bussen. I framtiden kommer nya tillämpningar att kräva mer bandbredd.

Denna rapport analyserar tre stycken Ethernet-protokoll med realtidskrav (AFDX, TTEthernet och Ethernet AVB). Utifrån analysen har en mjukvarustack baserat på AFDX designats och implementerats.

Prototypen använder ett koncept som kallas virtuella länkar för att dela upp den tillgängliga bandbredden. En virtuell länk är en statisk väg mellan sändande och mottagande nod. De virtuella länkarna schemaläggs periodiskt och begränsar bandbredden baserat på två parametrar som sätts för varje virtuell länk. Bandbreddsuppdelningen definieras statiskt för alla virtuella länkar. På så sätt garanteras en övre gräns för tiden det tar att överföra ett meddelande eftersom buffertstorlekarna i Ethernet-switchen kan bestämmas.

Protokollstacken testas med att överföra simulerade J1939-meddelanden i två experiment. Det första experimentet använder frekvensackumulering för att parametersätta de virtuella länkarna. Det andra experimentet inkapslar flera J1939-meddelanden i ett Ethernet-paket. Resultatet från experimenten var att inkapsling av flera J1939-meddelanden i ett enskilt Ethernet-paket är den mest effektiva lösningen.

En fördel med detta protokoll är att det kan användas med befintliga smarta Ethernet-switchar. Ett förslag hur lösningen gradvis kan introduceras ges som framtida arbete. Det behövs dock en utredning om det fysiska lagret, elektromagnetisk kompatibilitet, kabeldragning samt kontaktering. Slutsatsen för examensarbetet är att protokollet kan användas i framtida Ethernet-tillämpningar.

Preface

I would like to thank Scania for letting me conduct this degree project. I would also like to thank my supervisor at the Royal Institute of Technology Olof Hagsand for the advice and support during my thesis.

I further want to thank my supervisor at Scania Jan Lindman for initiating the subject and giving me advice and support during my thesis.

Last but not least I would like to thank all the wonderful people at Scania RESA

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1 Introduction

This chapter will give the background and an introduction to the problem and what the project will cover.

Controller Area Network (CAN) is the current communication system that is in use in Scania trucks. In the future improvement and development of the communication system will require high speed communication and robustness. Ethernet is one of several possible technologies that can meet this demand though there are many challenges ahead to realize it in a truck environment.

1.1 Problem Definition

Today's usage of CAN (Controller Area Network) is reaching its limits when it comes to bandwidth. The vehicle communication bus grows more and more complex for each day. The theoretical maximum bandwidth for a single CAN bus is 1 Mbit/s. In automotive applications it is limited to 125 kbit/s - 500 kbit/s. In the future more bandwidth is needed and new features require more bandwidth. High bus utilization is a problem and one way of reducing bus utilization is to go with higher bandwidth solutions.

A problem with Ethernet in a real-time vehicle network is the difficulty of determining response time and determinism. For example on a half duplex network the CSMA/CD access method is non-deterministic because if a collision is detected (two nodes are transmitting at the same time) the node will wait for a random amount of time before trying to transmit again. This creates problems because it is difficult to give real-time guarantees for something that waits a random amount of time.

With full duplex there is no access arbitration to the medium and as a result no collisions. One problem remains and that is unrestrained buffer contention in the switch and how to give guarantees of an upper bound on the latency when transmitting packets from source to destination.

When integrating the solution there are a couple of things to keep in mind regarding the product development process at Scania.

- Same software in all vehicles
- Incremental updates of ECUs (Electronic Control Unit)

- Backward compatibility
- Parallel releases
- Parallel verification

1.2 Goal

The goal is to investigate if and how an Ethernet solution could be implemented and adapted to Scanias in-vehicle network. The focus area is protocol implementation.

An investigation is made where different protocols are researched and evaluated for Scania adaptation. A protocol is selected and a simple demonstration of carrying CAN messages over an Ethernet backbone shall be made.

1.3 Delimitations

The report is not about the electrical layer and how the cabling should be done. Focus is on investigating suitable Ethernet protocols, developing a simple prototype and how the protocol can be implemented and how it could be adapted to Scanias in-vehicle network.

2 Background

This chapter will give the reader an introduction to real-time concepts, layered network architecture and give the reader the ability to understand the protocols that are involved in the investigation.

2.1 Real-Time Systems and Communication

A simple description of a real-time system is a system that has requirements to complete its work and deliver its services on a timely basis. Examples of such systems include telecommunications, digital control and signal processing systems.

The real-time systems can be found everywhere and provides important services. For example when we drive our car the systems control the engine and brakes. It is important that these systems function correctly and predictable.

A Real-Time communication network sends messages between different components in a real-time system [1]. The message consists of one or more units called frames, packets or cells. What they are called depend on the type of network and the nomenclature used.

There are two types of timing constraints in real-time communication. Hard timing constraints typically imply that the failure to meet a deadline can have fatal consequences. For example throttle control on an aircraft. If the movement of the throttles does not signal the engines to power up in time the plane could be in serious trouble.

A soft timing constraint typically implies that the failure to meet a deadline is undesirable. For example if a user is watching a live stream of a soccer game and there are a couple of video frames that miss their deadlines it might produce a short hiccup in the smoothness of the frame rate but its consequences will not be fatal. At worst the viewer is slightly annoyed.

In other words soft-real-time requirements have soft timing constraints and hard-real-time requirements have hard timing constrains.

A nondeterministic network have no guarantees for packet transmission, response time and packet delay variation. With a strictly deterministic network it is possible to produce an offline schedule for the packets sent in the network and verify the feasibility for the schedule before you run it. Something in between a nondeterministic and a strictly deterministic network is a network where it is possible to calculate an upper bound for the response time and the packet delay variation.

2.2 Network Layers

A common way of describing the communication in a network is to use a layered architecture. An architecture known the TCP/IP model was created by DARPA in the seventies. DARPA is an agency of the United States Department of Defense. The TCP/IP model is also known as the Internet model.

Different authors of books covering the TCP/IP model use either a four layer architecture or a five layer architecture. It has to do with whether the link layer covers the physical layer or if a hardware layer is assumed below the link layer [11]. The layered architecture explained here is the five layer model as depicted in Figure 1.

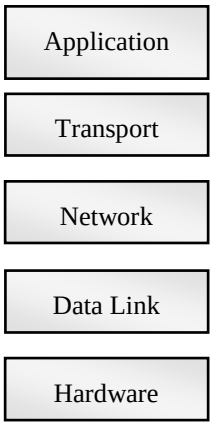


Figure 1. TCP/IP model

The Hardware layer is responsible for sending the individual bits on the wire from one node to another. The data link layer encapsulates groups of bits into frames from higher levels in the architecture. The network layer provides support for communication between networks. The network layer is not responsible for reliable transmission. This implies that it has no guarantee that the packets will arrive in a proper way. It is up to the transport layer to provide a mechanism to guarantee reliable service. Lastly the application layer is responsible for the process to process communication over the network.

2.3 Ethernet

Ethernet is a family of frame based networking technologies for local area networks (LANs) [2]. A LAN is a network that connects devices in a limited area such as a home, office buildings et cetera. Several connected LANs that spans a city or a larger area is called a Metropolitan Area Network (MAN). A MAN usually connects the LANs with a

high capacity backbone using fiber optical links. Described and of interest in this report are LANs.

A LAN can be used in a wide variety of topologies such as bus, line or star. It can work both in half-duplex and full-duplex mode. There are a number of different transmission mediums that can be used such as coaxial, copper and fiber optic cable. The LAN technology was developed at Xerox PARC in the seventies. The first IEEE 802.3 standard was published in 1983 and called 10Base5. 10Base5 has a bandwidth of 10 Mbit/s over thick coax cable. The standard is continuously evolving and today there are Ethernet controllers and switches available with a capacity from 10 Mbit/s [2] to 40 Gbit/s [3].

2.3.1 Topology

Two common topologies in a LAN are bus and star. In bus based architectures the nodes are connected directly to the cable as depicted in Figure 2.

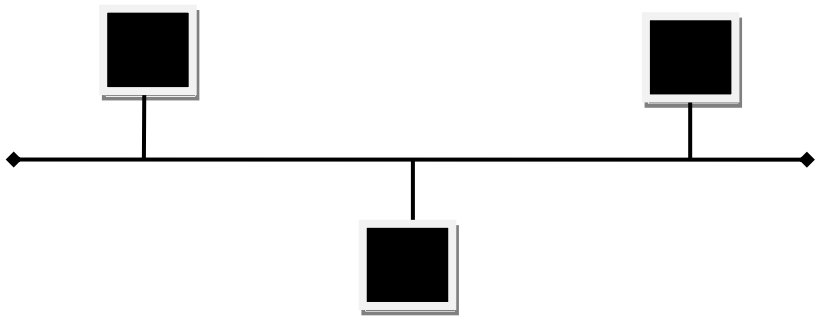


Figure 2. Ethernet bus topology

The channel is shared between all the nodes connected to the cable and some sort of access control is needed. The most common method of access control for a bus based architecture is CSMA/CD.

CSMA/CD stands for Carrier Sense Multiple Access with Collision Detection. For a station to transmit on the shared medium, the station waits for a quiet period. If a message that is sent from one node collides with a message from another node, both nodes will continue to transmit for an additional predefined period. This is done to ensure that all stations are able to listen to the collision. If a collision is detected the station will not try to resend the message for a random amount of time.

The problem with CSMA/CD is that under high traffic situations the throughput and maximum delay can become unacceptable. It is also nondeterministic due to the random

wait that is conducted when a message collision occurs [9]. In a star based architecture the nodes are connected to a central switch which connects the segments with each other as seen in Figure 3. Switched Ethernet is the most common implementation for LANs today.

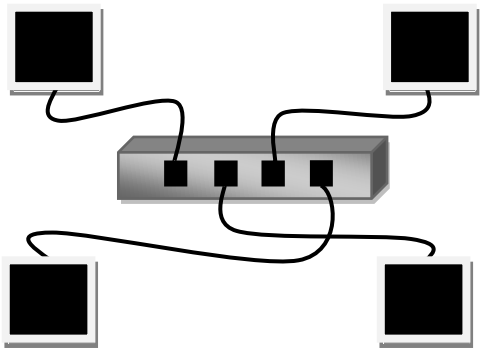


Figure 3. Ethernet star topology

A huge benefit with a switch is that each segment is able to run in full duplex operation. With full duplex operation each station can transmit and receive at the same time. Consequently there is no need for an algorithm to check for collision and wait for the medium to be silent.

2.3.2 Switch Types

Layer 2 switches (data link layer) use the media access control (MAC) destination address as a source to forward packets. The switch processes the packets when they arrive at a switch port.

A standard Ethernet switch dynamically updates the MAC destination table based on the traffic that flows through the switch. All entries in the table have an age associated with it. If no packets are received for a specific flow the entry will be deleted.

Different types of switches have an impact on latency [10]. A Cut-Through switch waits until the MAC destination address is received and copied into the internal buffer in the switch. It then looks in the MAC filter table to determine the outgoing port. The packet is forwarded as soon as the switch reads the destination address. This results in decreased latency but invalid packets are also forwarded.

The Store and Forward switch waits until the entire packet is received. The entire packet is copied into the internal buffer and the switch calculates the cyclic redundancy check (CRC). If the packet contains an error or has an invalid size the packet is dropped. After the CRC is calculated and the packet contains no error the switch checks the MAC filter

table for the destination address to determine the outgoing interface. Modern switches are of Store and Forward type.

2.3.3 Protocol Layout

There are several types of Ethernet frame formats. The different types have different formats. The Ethernet version 2 is the most common type used today. The frame format explained in this project is the Ethernet version 2 packet and frame format and is depicted in Figure 4.

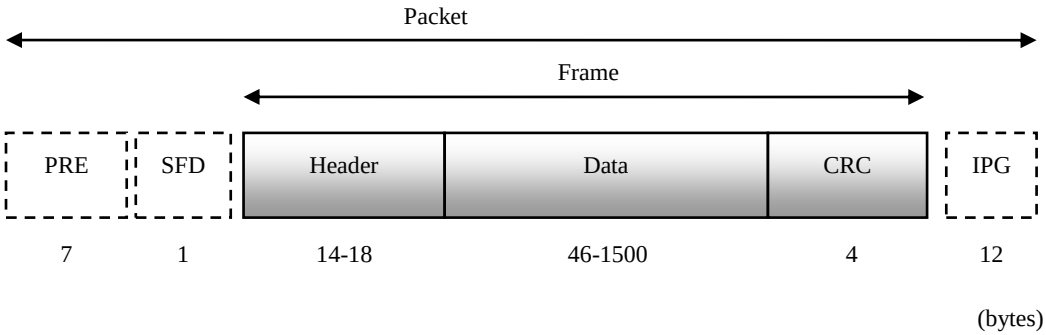


Figure 4. The structure of an Ethernet packet

The packet format [2] has 8 bytes before the frame and consists of the preamble field and the start frame delimiter. The preamble field is 7 bytes and is used to signal the transmission of a new packet, it contains alternating 0s and 1s and is used to synchronize the controller. The Start Frame Delimiter (SFD) is 1 byte and contains the sequence 10101011 (0xAB). It is used to denote start of frame. The header of the frame is either 14 bytes or 18 bytes as depicted in Figure 5. Virtual LAN (VLAN) tagging that is specified in [5] increases the maximum frame size with 4 bytes. VLAN adds a 4 byte field between the source address and the length/type field. Otherwise the header consists of the destination, source and the length/type field.

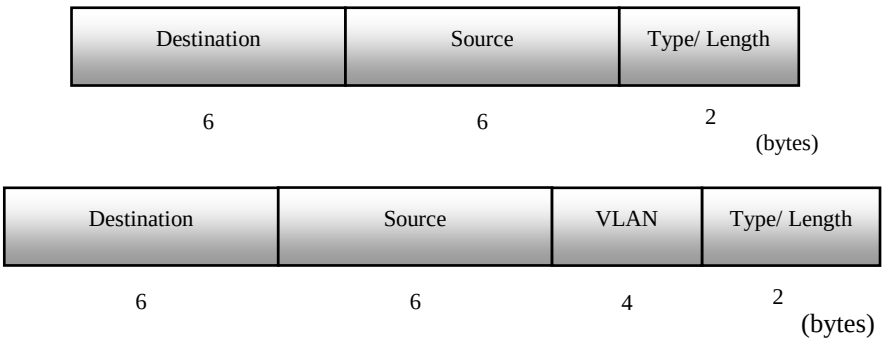


Figure 5. Two Ethernet headers

The MAC-address fields are 6 bytes each. One for the destination address and one for the source address.

The least significant bit in the most significant octet in a MAC-address field is used as an address type designation bit. If the bit is 0 it indicates that the field contains an individual address. If bit is 1 it indicates that the field contains a group address that indentifies none, one or more or all of the stations (multicast). The source field least significant bit is reserved and set to 0. The second bit in a MAC-address field is used to distinguish between locally or globally administered addresses. For a globally administered address the bit is set to 0 otherwise 1. For broadcast bit is set to 1.

So to recap there are basically two type of MAC addresses individual or group/multi-destination. Individual addresses are associated with a particular station on the network. Group/multi destination addresses are two kinds. Either they are multicast-group address or broadcast. The broadcast address is predefined to all ones and defines all stations on the LAN.

If VLAN tagging is used 2 bytes of the VLAN field are used as the Tag Protocol Identifier (TPI). A special value is used to identify it as an 802.1Q frame (0x8100). The other 2 bytes are used as a 3-bit priority field, a 1 bit field that is always set to 0 for Ethernet switches and a 12 bit VLAN identifier field that is used to identify which VLAN the frame belongs to.

The length/type field is 2 bytes. If the value is less than or equal to 1500 the field indicates the number of data bytes in the following data field. If the value is greater than or equal to 1536, the field indicates the type of client protocol that is carried in the data field.

Originally the data field supported payloads between 46-1500 bytes. Today there are extensions called jumbo frames and super jumbo frames. A jumbo frame can carry up to 9000 bytes of payload and a super jumbo frame up to 64 000 bytes. If the length is less than the minimum, a pad field is added after the data field. The minimum data field size of 46 bytes is required for correct CSMA/CD protocol operation. If the payload is less than 46 bytes the pad field is used up to a minimum of 46 bytes for the data + pad field. The CRC is computed as a function of the frame contents except the preamble and SFD.

Inter Packet Gap (IPG) according to [2] is used to allow a minimum idle period between transmission of frames. It is used so the devices can prepare for reception of the next frame. The minimum IPG is specified as 96 bit-times which is equivalent to the time it takes to transfer a 96 / 8 = 12 byte field. A more detailed description can be found in [2].

2.4 Controller Area Network

Controller Area Network (CAN) was originally designed for automotive applications. It was introduced in 1986 by Robert Bosh GmbH at the Society of Automotive Engineers (SAE) congress. Prior to CAN automotive manufacturers connected devices with point-to-point links as seen in Figure 6. The added weight and the significant amount of wiring resulted in expensive routing. To reduce cost and wiring a better vehicle network was needed.

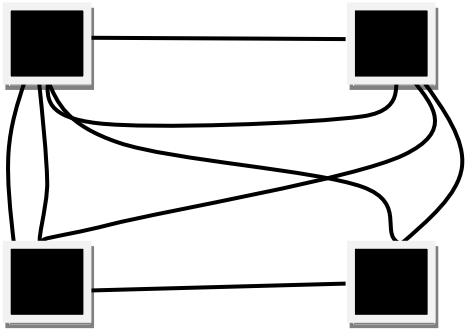


Figure 6. Point to point network

The standard [5] for CAN was published in 1993(CAN 2.0 A) and specified a maximum transfer rate of 1 Mbit/s. In 1995 an extension was made that increased the CAN identifier field from 11 to 29 bits (CAN 2.0 B). The standardized application layer J1939 uses the extended CAN format and it is also the format that is described in this report.

It is not only in the automotive industry that CAN is used. It is popular in the textile industry and is also found in ships, trains and aircrafts to name a few.

2.4.1 Communication

The CAN bus is used for communication between ECU's (electronic control units). In a truck there are different control units for different parts. For example engine control, transmission and antilock braking. The ECU's might need sensor data from sensors located in the vehicle and the CAN standard was developed to fill this need.

The CAN network is a serial bus network (line topology) as depicted in Figure 7. The messages are generally not addressed to a specific node but broadcasted. It is up to the individual node if it is interested in the message or not.

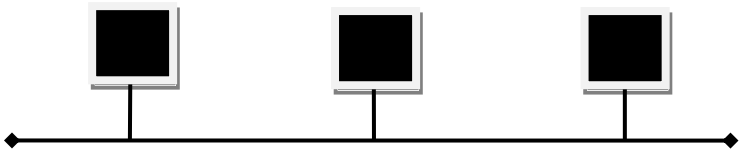


Figure 7. CAN serial bus

If a node wants to transmit on the bus it waits until the bus is free. All messages have an identifier that also works as the priority of the message. The maximum payload for a CAN message is only 8 bytes. It was designed to be used to send signals to trigger events or to send sensor data.

The CAN network uses wired-AND logic and the binary model of dominant and recessive bits. A dominant bit is a logical 0 and recessive is a logical 1. If at the same time a node transmits a dominant bit (0) and another node transmits a recessive bit (1) a dominant (0) is seen on the bus, the result is the logical AND between the two.

2.4.2 Protocol Layout

The CAN frame format explained here is the extended format (CAN2.0 B) [5]. The main difference between the standard format (CAN2.0 A) and the extended format is that the id field has been extended to 29 bits instead of 11 bits in the original standard. The application protocol SAE J1939 is also based upon the extended format. The CAN frame format is depicted in Figure 8.

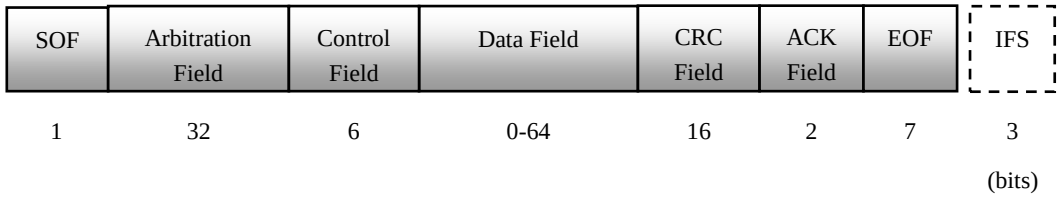


Figure 8. CAN frame format

Before the frame a 1 bit Start of Frame (SOF) is sent as a hard synchronize mechanism. The arbitration field consists of an 29 bit Identifier divided into two part Identifier A (11 bits) and Identifier B (18 bits) and three one bit fields called SRR, IDE and RTR. The IDE bit identifies whether the frame is a standard frame or an extended frame. See the ISO 11898 Part 1 for a more detailed description.

The 6 bit control field consists of 2 bits called r0 and r1 and is reserved. The other four bits include the Data Length Code (DLC) and is used to tell the size of the following data field. The data field can be anything between 0 to 8 bytes large. The CRC field consists of a 15 bit CRC sequence followed by a 1 bit CRC delimiter. The ACK field contains a 1 bit ACK slot followed by a 1 bit ACK delimiter. The transmitting node sends these two bits recessively and it expects at least one of the receivers to acknowledge the frame.

The frame is acknowledged if the receiving node receives the message without errors it will then overwrite the ACK slot with a dominant bit. After the ACK field the end of

frame field (EOF) that denotes the end of the CAN frame. The Inter Frame Space (IFS) separates messages from each other. It is the minimum amount of space between adjacent frames.

2.4.3 Arbitration

When arbitrating all the transmitters compare the level of the bit transmitted with the level that is monitored on the bus. If the bits are equal the node continues. If they are not equal the node stops transmitting. As a result the CAN message with the highest priority will succeed and the node that is trying to transmit the lower priority message will sense this and stop. All messages that are sent are available to all nodes on the network and it is up the each node if it is interested in the message.

2.4.4 Bit-Stuffing

The bit encoding in CAN is non-return to zero (NRZ). With NRZ the signal will remain at 0 for multiple bits of 0 and the other way around. To prevent transceivers and receivers to lose synchronization a stuff bit is used. The bit stuffing causes a variable packet size that depends on the bit representation of the packet.

Bit stuffing in CAN is triggered when five bits of the same type is sent in a row [6]. An extra bit of the opposite polarity is then sent by the transceiver when it detects that it has sent five bits of the same polarity. Make a note of that the stuff bit is included in the computation. This implies that the worst case pattern is not five bits of one polarity followed by five bits of the opposite polarity and so on but an initial five bits followed by four bits of opposite polarity as depicted in Figure 9.

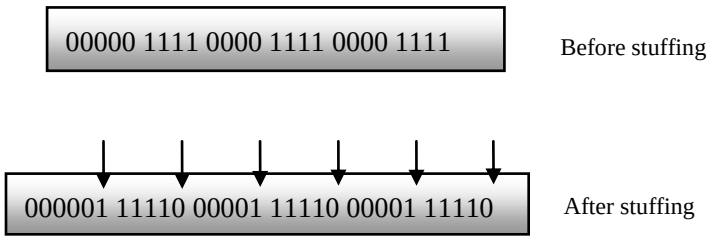


Figure 9. Worst case bit stuffing pattern

Not all bits in a CAN frame is affected by the bit stuffing. The arbitration field, control field, data field and the CRC field are affected by the bit stuffing. A zero payload CAN frame has 54 (out of 67) bits affected by bit stuffing. The worst case number of stuff-bits [6] is

$$\left\lfloor \frac{54 + 8d - 1}{4} \right\rfloor = 13 + 2d$$

where d is equal to the data payload in bytes. As a result the minimum CAN frame can be anywhere from 67 bits to 80 bits depending on the bit sequence.

2.5 J1939

J1939 is the application protocol standard Scania uses when sending messages on the CAN bus. J1939 defines message identifiers and the message content. Its focus was primarily to standardize the messages for the engine, transmission and brake applications but has later been extended to various functions and applications. It was created in the beginning of the nineties by a committee called Society of Automotive Engineers (SAE).

2.5.1 Protocol Layout

The J1939 frame as seen in Figure 10 uses the 29-bit ID field that is part of the arbitration field in CAN to store PGN (parameter group number) and source address [7]. A parameter group is assembled of parameters defined in the J1939 standard. For example oil temperature, vehicle speed and so on. The PGN is used to identify the content of the data field.

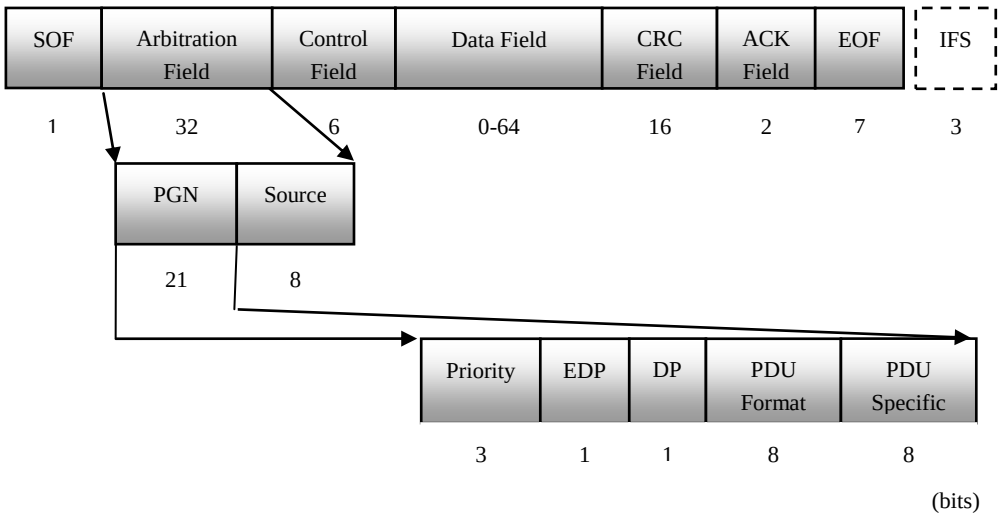


Figure 10. The structure of J1939

2.5.2 Parameter Group Number

The PGN consists of a 3 bit priority field, the value 0 is the highest priority and 7 the lowest. Following the priority field is the EDP (extended data page) and the DP (data page). The extended data page bit is used together with the data page bit to determine

the structure of the CAN identifier of the can data frame. The definitions for all the combinations can be seen in [7]. The PDU format is an 8 bit field and is one of the fields used to identify the parameter group number. Parameter group number is used to identify or label commands, data, requests and acknowledgments. A parameter is data such as engine rpm. It is common to group parameters together to utilize all the 8 bytes payload in a single CAN frame.

PDU specific field is 8 bits and can be a destination address, group extension. It depends on PDU format, if the value of the PDU format is below 240 (0xF0) the PDU specific field is a destination address. The destination field contains the specific address to which the CAN message is sent. The value 255 is a global destination address and requires that all the nodes listen and respond. If it is between 240-255 (0xF0-0xFF) then the field contains a group extension. The group extension extends the number of parameter group numbers. Without the group extension you have 240 possible parameter group numbers per data page. There are two possible data pages (DP field can be 0 or 1) so that gives a total of

$$240 * 2 = 480\ PGNs$$

With the group extension the PDU specific field together with the four least significant bits in the PDU format field provides

$$2^{12} = 4096\ PGNs$$

The total parameter group numbers are

$$240 * 2 + 2^{12} * 2 = 8672\ PGNs$$

When more than 8 bytes is needed for a Parameter group the data is split into multiple CAN data frames. Examples of Parameter groups can be found in [8].

2.5.3 Protocol Data Unit

A J1939 PDU (protocol data unit) [7] consists of the PGN, Source and the data field as depicted in Figure 11. There can only be one PDU per CAN data frame although it can take more than one CAN data frame to send all the data for one PGN.

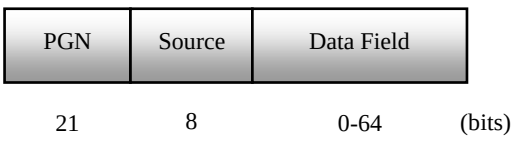


Figure 11. The J1939 Protocol Data Unit

2.6 FlexRay

FlexRay is an automotive communication protocol. It was designed as an improvement over CAN and supports high data rates up to 20 Mbit/s. The protocol supports both time triggered and event triggered communication. It uses a bus in a comparable way to CAN. It supports dual redundancy and combined with the time triggered communication it meets the reliability requirements for future applications such as brake-by-wire. It is currently in use today by Audi, BMW to name a few [43].

2.7 Scania CAN Network

The Scania CAN network consists of three communication buses (green, yellow and red). It uses J1939 as described in section 2.6. The buses are connected to a gateway called Coordinator (COO) as depicted in Figure 12.

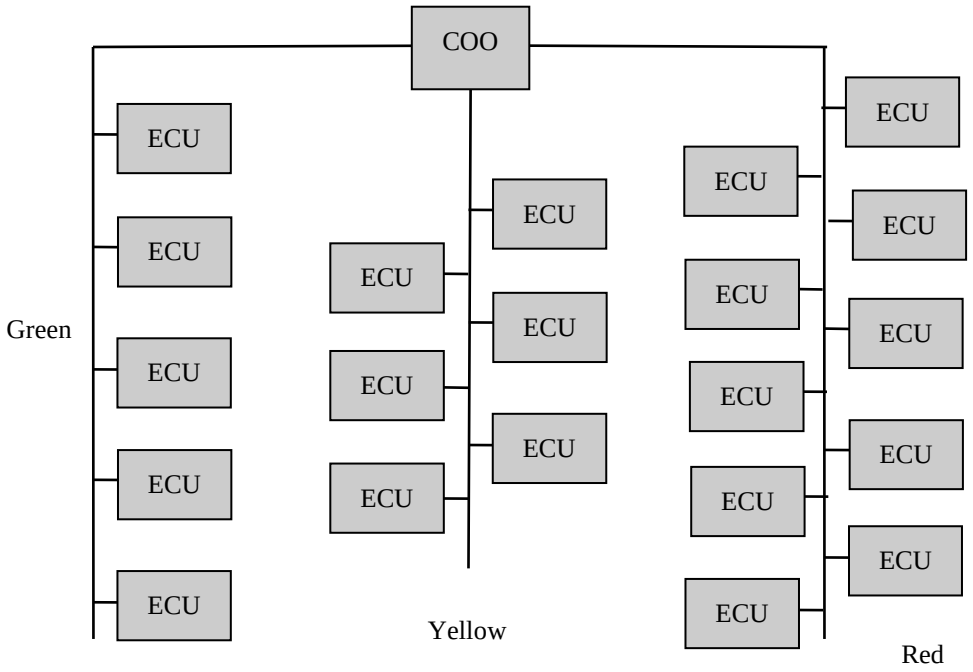


Figure 12. Scania CAN network

The Coordinator gates messages between the different buses. The buses are color coded based on how time critical the communication on the bus is. The red bus is the most time critical. It handles for example the communication between the engine, transmission and brakes. The yellow bus is used for less time critical communication and the green bus is used for the least time critical communication. Today the network

load on the buses is reaching the limit of what is possible using the current CAN bus. My suggestion is to create a converged Ethernet backbone with nodes capable of high bandwidth transmissions.

High bandwidth applications such as infotainment and driver assist system (camera system et cetera) require an updated architecture. To converge the communication more buses should be connected through the use of gateways. If Ethernet is adopted it could be used for the diagnostic interface instead of the current interface over CAN. Diagnostics could then be performed using a notebook with a standard TCP/IP stack. There is currently a standard in development for diagnostic over IP called DoIP [42]. Flashing of ECU's is also a bottleneck on the current CAN bus that could be improved using Ethernet.

The architecture requires a suitable Ethernet protocol for communication over the Ethernet backbone. In the following chapter different Ethernet solutions are described and explained. The goal is to find a suitable protocol for real-time communication.

3 Available Technology

This chapter explains the three different Ethernet technologies studied in this project. A summary of the difference of the protocol is described in chapter 3.4

When selecting the Ethernet protocols it is important that they have real-time characteristics, solutions for the unrestrained buffer contention in the switch and how to give guarantees of an upper bound on the latency. The three selected protocols are AFDX, TTEthernet and Ethernet AVB. AFDX is selected because it is an established standard currently in use in the airline industry. TTEthernet is an interesting technology that supports time triggered communication and can be an alternative to the time triggered protocol FlexRay that is proposed as the successor to the CAN bus. Last but not least Ethernet AVB, a standard from IEEE and aimed at the consumer/professional audio video market that has the capability to hit a large market and as a consequence create lower cost Ethernet hardware with real-time support.

3.1 AFDX

Avionics Full Duplex Switched Ethernet (AFDX) is specified in ARINC 664 Part 7. It is a standard for a deterministic data network based on 10 or 100 Mbit/s switched Ethernet. It was initiated by Airbus in the design and creation of the A380 aircraft. The predecessor to AFDX, ARINC 429 is a point to multipoint bus system that supports one-to-one or one-to-many connections. AFDX is an improvement compared to ARINC 429 due to the higher data transfer rate (approximately one thousand times faster) and less wiring is needed which reduces wiring runs and the weight [12].

The most important elements of an AFDX network are

- AFDX End System: The end system is the interface between the subsystems (for example flight control computer) and the network.
- AFDX Switch: A full-duplex switch. The switch forwards Ethernet frames to the correct destination.
- AFDX Virtual Links: A virtual link is a unidirectional virtual connection from one-to-one or one-to-many End Systems.

3.1.1 Supported Traffic

AFDX supports rate constrained traffic. The AFDX network provides an upper bound on latency and determinism [18] through modifications and restrictions to the Ethernet protocol in the following way

- Bandwidth partition: Maximum data packet size and scheduling of packets to allow guaranteed bandwidth
- Defined packet order: Packets are received in the same order they are sent
- Dual Redundancy: An end station transmit the same packet out of two ports

The communication protocol is derived from IEEE 802.3 MAC addressing, User Datagram (UDP) and Internet Protocol (IP).

3.1.2 Virtual Links

Virtual links partition the switched network into communication channels with a predefined link bandwidth and scheduling time. The virtual link is unidirectional and uses a 16-bit identifier that is part of the MAC destination address as seen in Figure 13. The switches are configured to route packets based on the virtual link ID. One Virtual link will have one or more predefined end systems that the switch sends packets to. A virtual link can only have one sending end system but multiple receiving end systems [13]. A notice can be made that all MAC addresses are locally administered and of multicast type according to the IEEE 802.3 standard (the second and the least significant bit of the most significant address octet is set to 1) .

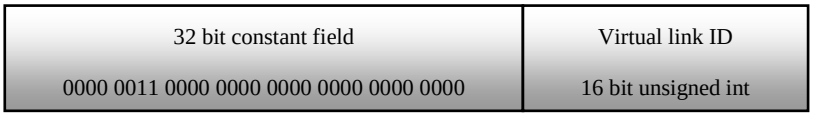


Figure 13. AFDX MAC destination address

The virtual link has two parameters

- Bandwidth Allocation Gap (BAG) , the BAG value restrict how often the virtual link is scheduled (how often it is possible to send a message on the virtual link). In the AFDX standard the valid range for the BAG value is in powers of 2 from 1 to 128 ms.
- Lmax is the largest Ethernet frame size the virtual link can transmit (IP layer takes care of segmentation and reassembly).

Figure 14 below exemplifies two virtual links in an AFDX network.

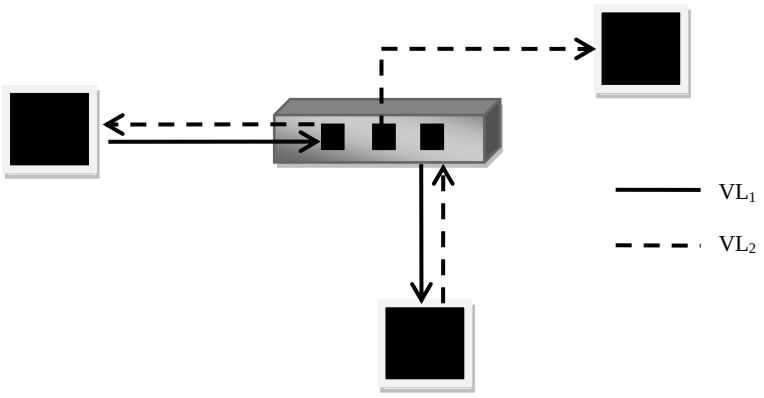


Figure 14. AFDX virtual link routing

As an example a virtual link with a BAG of 8 ms and an Lmax of 200 bytes. The maximum bandwidth in kbit/s on the virtual link is

$$\frac{200*8}{8ms} = \frac{1000}{8} * 200 * 8 = 200\ kbit/\text{s}$$

Choosing an appropriate BAG for multiple messages transmitted through the same virtual link can be done in the following way. If you have three messages m_1, m_2 and m_3, with a frequency of 15, 30 and 40 Hz, you add their frequencies together

$$15 + 30 + 40 = 85\ Hz$$

The period for a frequency of 85 Hz is 11.8 ms. The closest BAG that is less than 11.8 ms is 8 ms. A period of 8 ms corresponds to a frequency of 125 Hz.

If $m_3$is the message with the highest frequency of 40 Hz and its deadline is equal to its period (25 ms). The worst case scenario happens if all the messages arrives within a single scheduling period. Message m3 is still scheduled and transmitted before its deadline because the virtual link scheduling frequency (125 Hz) is larger than the combined frequency (85 Hz) of the three messages as seen in Figure 15 below.

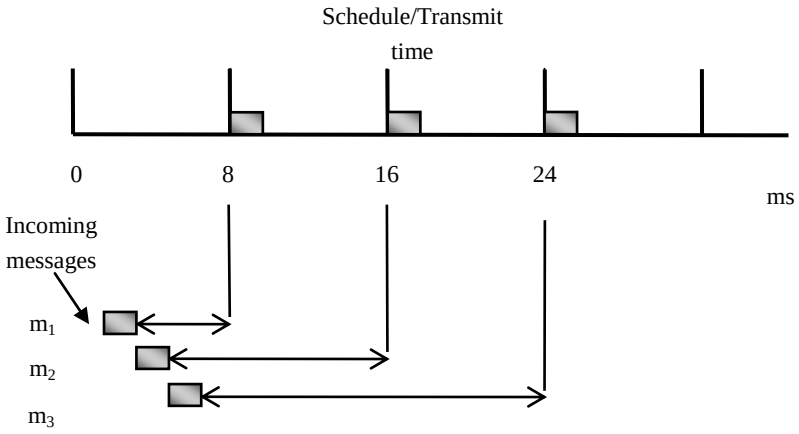


Figure 15. AFDX scheduling three messages

Assured service is an important concept for the AFDX network. The bandwidth and the end-to-end latency for each virtual link are guaranteed. The specification does not cover guarantee of packet delivery. It is up to the individual application to handle transmission acknowledgement and retransmission requests [15].

3.1.3 Virtual Link Scheduling

The virtual link scheduler in each end system is responsible for the transmit schedule. Applications send messages to the communication ports. The messages are encapsulated within the UDP, IP and Ethernet frames. It makes sure that the bandwidth limit based on the virtual link BAG and Lmax parameters are under control and it multiplexes all the virtual links as depicted in Figure 16. The multiplexing of virtual links can introduce jitter if they are scheduled in the same time slot [12].

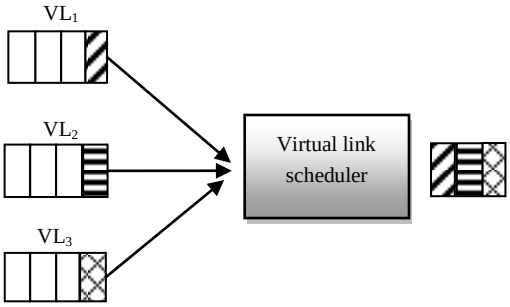


Figure 16. AFDX virtual link scheduling

3.1.4 End System and subsystems

The end system in an AFDX network is the interface between the subsystems and the AFDX switch. One computer system encapsulates multiple subsystems and an end system as seen in Figure 17. The subsystems are partitioned and isolated from each other. It is implemented by restricting the address space and limiting the amount of processor time each subsystem can use. Actuators and sensors are connected to each subsystem, the applications running in each subsystem reads data from the actuators and sensors and transmits messages to the end system.

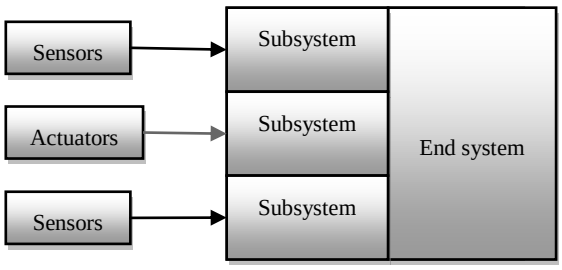


Figure 17. AFDX computer system

An AFDX network is dual redundant as depicted in Figure 18. The networks are called the A and B network. When the end system receives a message on either the A or the B network the message is first controlled by the integrity checker. It detects and eliminates invalid frames. The redundancy management is responsible for determining whether it should drop the packet or pass it to the upper layer of the protocol stack. This is based on if it has already received a packet with the same sequence number and associated with same virtual link. The applications communicate with each other by sending messages using communication ports. End systems are identified with two 8-bit IDs: the Network ID and Equipment ID. The identifiers are used to create the source MAC address and the unicast IP address [14].

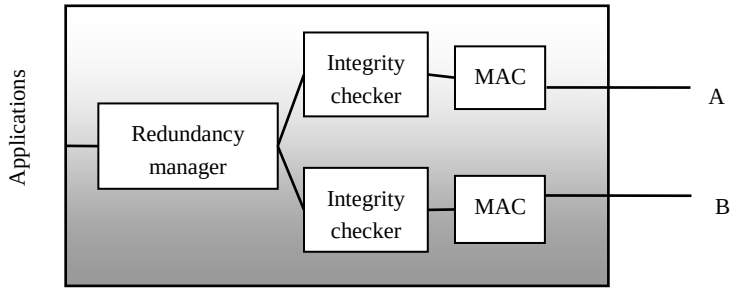


Figure 18. AFDX end system

3.1.5 Communication ports

There are three types of ports described in the AFDX standard. They are queuing, sampling and service access ports (SAP) [12].

The queuing port is message oriented. The queue size is preconfigured and the queue will accept messages until it is full. A transmitting queuing port uses a FIFO based method. Messages are appended to the queue and removed at each time instant the virtual link connected to the port is scheduled. If there are no more messages in the queue the transmission will stop. The receiver queuing port appends messages to the receiver port queue. It does not overwrite the current messages compared to the sampling port and when the application using the port receives a message it is removed from the queue port as seen in Figure 19.

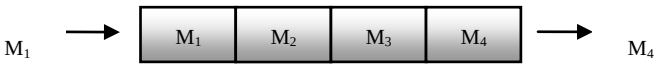


Figure 19. AFDX queuing port

The sampling port can be realized as a queuing port with a capacity of one message as depicted in Figure 20. The sampling port can be read multiple times because the message is not removed from the buffer. If a message is sent it overwrites the old message in the buffer. A message is sent at each instant the virtual link is scheduled. If the transmitting application has not written a new message to the port the old message is sent. Each sampling port has a freshness indicator that tells when the last message was received. This way an application can tell whether the sending node has stopped sending or if it is sending the same message repeatedly.

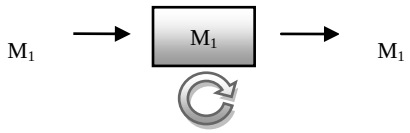


Figure 20. AFDX sampling port

The service access ports are used for communication between AFDX components and non AFDX components. The applications using service access ports create the connection by specifying the IP destination address and UDP port number dynamically. The communication ports are carried by the virtual links. At design time you assign ports to virtual links based on the type of traffic you send through the port.

3.1.6 AFDX Switch

The AFDX switch forwards packets according to a static MAC-table. With the AFDX switch each MAC address in the table correspond to a virtual link identifier.

At a minimum a managed switch with a programmable MAC-table and the ability to statically define the table is needed. The Rx and Tx buffers store packets in a FIFO order. The CPU move packets from the incoming buffer and examines the destination MAC-address (virtual link identifier). It finds the virtual link identifier entry in the table and route the packets to the outgoing buffer of the correct port.

Certified AFDX switches also contain functions for filtering, policing and monitoring. The filtering is based on frame integrity, frame length and valid destination in the address table. Traffic policing is based on a token bucket algorithm. A token bucket algorithm keeps a token account for each virtual link. The account is credited with tokens as time progress. This is based on the BAG and the maximum size of a packet for the virtual link. When a frame is received it checks the account and if enough credits are available the packet is sent and credits debited. The amount of token is limited by the maximum jitter that is allowed. The monitoring function is used to log switch operation and the health of the network. It is the job of the traffic policing to make sure that no virtual links routed through the switch exceeds its maximum bandwidth [15].

3.1.7 Frame Format

The Ethernet payload for an AFDX frame as seen in Figure 21 consists of the IP packet (header and payload). The IP packet payload consists of the UDP header and payload. The UDP payload consists of the AFDX message and a one byte sequence number. The IP payload supports fragmentation control for large UDP packets using queuing ports. The IP header contains a destination end system id, partition id (which subsystem partition it want to address) or a multicast address. If it is a multicast address the destination IP address will contain the virtual link id. The UDP header contains the source and destination port number (communication port). The sequence number is used for missing packet detection and the redundancy management in the receiving end system. For the specifics about AFDX messages payloads in avionics see [14]

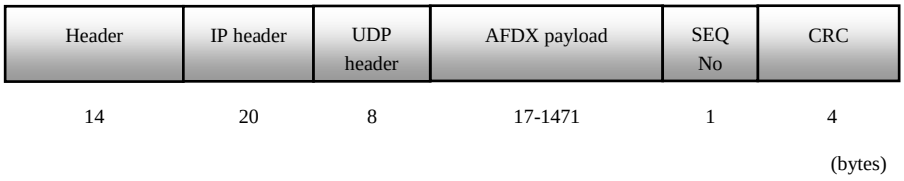


Figure 21. AFDX Ethernet frame

3.1.8 Current Status

AFDX is currently in use in the Airbus A380, A400M aircraft and Boeing 787 Dreamliner [16]. It is used as the backbone between flight computer, fuel system, engine control and others.

In a paper by NASA [17] a laboratory experiment was performed using a Cisco (Catalyst 2900) switch. It was shown that the switch is capable of performing 30% from the AFDX specification of a maximum jitter of 500 μs.

At the SAE 2011 World Congress and Exhibition in April a paper was presented [19]. They did a comparison between CAN, FlexRay and Ethernet (AFDX) for ABS systems. It was shown that a 100 Mbit/s AFDX network achieved identical performance compared to a 10 Mbit/s FlexRay solution.

3.2 TTEthernet

TT-Ethernet was the name of a research project conducted by the Real-Time System Group at Vienna University of Technology in 2000. The academic project presented a time triggered solution over Ethernet hardware. The goal was to produce a solution for safety-critical real-time systems in automotive, avionics and railway domains. [25]

TTEthernet is a shared development involving TT-Tech and Honeywell that continued and improved the previous academic research project. It introduced scalable fault tolerance and support for communication with different real-time requirements. As a result three different traffic classes were introduced (time triggered rate constrained and best effort traffic). The protocol supports fault tolerant configuration in a similar way to the AFDX protocol with two ports per node and two independent switches.

3.2.1 Supported traffic

TT-Ethernet supports three types of traffic classes

- Time triggered traffic (TT)
- Rate constrained traffic (RC)
- Best effort traffic (BE)

Time triggered communication sends traffic based on global synchronized time. The time triggered packets are sent at predefined times and take priority over all other traffic types in the network. Messages from higher layer protocol like IP or UDP can be made time-triggered without modification to the messages themselves. The actual overhead from the protocol that enables time triggered traffic is sent in special messages. TTEthernet protocol with time triggered communication is as a result only concerned about when a message is sent not what specific content the message has. Time triggered traffic is used for applications that require low latency, little jitter and high deterministic behavior [20].

Rate constrained messages are used for applications with less stringent requirements than time triggered communication. The rate constrained traffic supported in TTEthernet is identical to the previous described technology AFDX. The AFDX standard segments the network into virtual links with predefined bandwidth limits, the traffic is shaped with a periodic leaky bucket in each end station. This creates a low upper limit on the buffers in each switch and a bounded latency on each virtual link. The rate constrained traffic is not sent based on a global synchronized time. A rate constrained message can suffer some delay if a time triggered message is transmitted via the same outgoing port at the same time [20].

Best effort traffic has the lowest priority. Both rate constrained and time triggered traffic has priority over best effort traffic that can be delayed or discarded. No guarantees are given and switches can drop messages if the buffers overflow. Best effort traffic should use some sort of acknowledgement such as TCP/IP otherwise it is possible to lose messages [20].

3.2.2 Time Triggered Synchronization

The time synchronization is a significant part to support time triggered traffic. The global time synchronization in TT-Ethernet uses frames called protocol control frames (PCF) to synchronize the nodes with each other. The synchronization domain is periodically resynchronized in intervals called integration cycles. Such a cycle could be one millisecond but depends on the amount of the acceptable clock drift [20]. A synchronization domain in TT-Ethernet contains three types of devices

- Synchronization Master
- Synchronization Client
- Compression Master

It is usually the end devices that are synchronization masters or clients and the switches compression masters. The synchronization is based on a simple two step approach. The synchronization masters is used as a base clock that transmits clock control messages to the compression master as seen in Figure 22 and 23. In first step the synchronization masters send clock control messages to the compression master. In the second step the compression master calculates the global time by averaging the time of all incoming frames from the synchronization masters [26]. A new protocol control frame is sent to all synchronization clients and masters which is used for resynchronization of the local clocks. All the nodes updates the local clock with the new global time received [21]

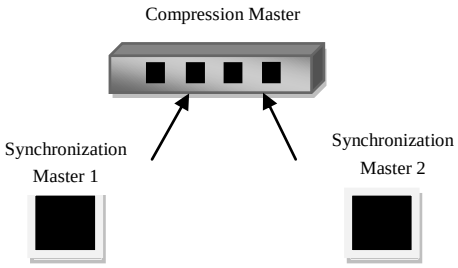


Figure 22. TTEthernet synchronization step 1

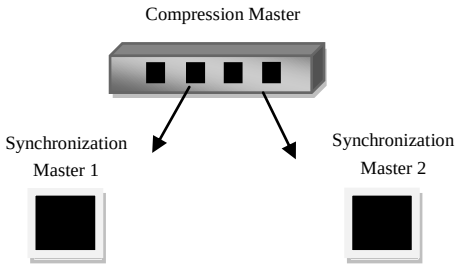


Figure 23. TTEthernet synchronization step 2

3.2.3 TTEthernet Switch

The TTEthernet switch can differentiate between time triggered traffic and other types of traffic by using the content of the Ethernet destination address [22]. When other traffic types such as rate constrained and best effort traffic is mixed it is important that lower priority traffic does not interfere with time triggered traffic. There are three different integration methods that is used when contention occurs on the outgoing ports

- Preemption
- Timely Block
- Shuffling

A Preemptive method preempts low priority traffic if a time triggered message is scheduled at the same time instant. Such a method provides high real-time quality because the outgoing ports for a time triggered message is free at the same instant as the time triggered message arrives. A negative aspect is the generation of false messages due to truncation.

Timely Block makes sure that the port is free based on the amount of time it takes to send a low priority message. If it is calculated that the low priority message intrudes on the global time when a triggered message is scheduled it is blocked. It provides the same real-time qualities as the preemptive method but may be resource inefficient.

Shuffling delays the high priority message if a low priority message is already transmitting. Such a method provides resource efficiency but low real-time quality.

In the paper *TTEthernet Dataflow Concept* [22] it is stated that TTEthernet uses timely block and shuffling but prototypes of preemptive switches exists.

A traffic schedule for the time triggered communication needs to be uploaded to all the switches in the network that have connected devices using time triggered traffic. The switch is reserved for time triggered traffic at the instants defined in the schedule.

As an example if three nodes send a mix of time triggered, rate constrained and best effort traffic the following can occur. The switch has received the best effort message from node 2 but a scheduled time triggered message from node 1interrupts the transmission of the best effort message. During the transmission of the time triggered message a rate constrained message from node 3 is received. The best effort message has to wait because it has lower priority than rate constrained traffic. The final serialization of the messages to node 4 is depicted in Figure 24.

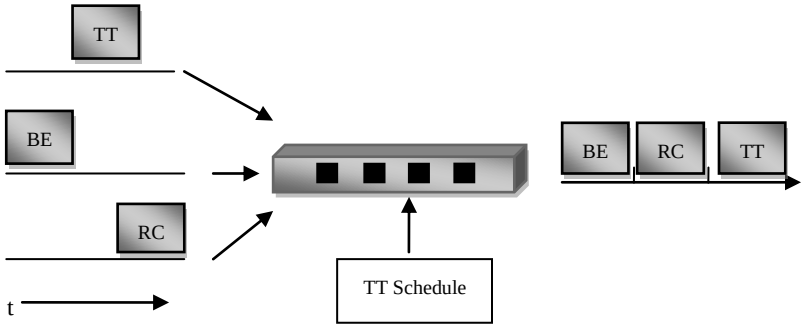


Figure 24. A TTEthernet traffic cycle with TT, BE and RC traffic

3.2.4 Frame Format

The frame format is similar to the AFDX except that it has not standardized that the payload is an UDP/IP packet. The MAC destination address is used to identify critical traffic (time triggered and rate constrained). It consists of a 4 byte CT-Marker to determine traffic type and a 2 byte CT-ID to determine message (virtual link id if traffic is AFDX) [23] as depicted in Figure 25.

Specific time triggered information is carried in special frames called Protocol Control Frame (PCF) [21]. They are identified with the type/length field set to 0x891d. The PCF contains information used to synchronize the devices in a TTEthernet network. Both the PCF and the actual time triggered messages are sent with broadcast.

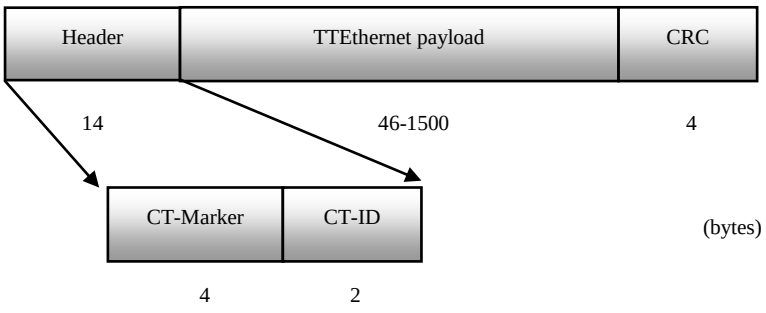


Figure 25. TTEthernet frame using TT-traffic

If AFDX frames are carried in a TTEthernet network it uses the same format as described in section 3.1.

3.2.5 Current Status

TTEthernet has been proposed as a new Society of Automotive Engineers (SAE) standard called AS6802. It is currently under development as of 2011[21]. The proposed SAE standard called AS6802 has several supporters for example Lockheed Martin, Bombardier, Honeywell and BAE Systems to name a few.

A comparison between FlexRay and time-triggered Ethernet solution has been made [24]. The results showed that time-triggered Ethernet is a suitable replacement of a current in-vehicle network.

TTEthernet is used as the backbone in NASA's Orion crew exploration vehicle. The Orion vehicle is the currently under development and is the successor to the recently retired space shuttle [25].

3.3 Ethernet AVB

Ethernet AVB is the IEEE take on a real-time Ethernet solution. AVB stands for Audio Video Bridging and the original work was carried out by an 802.3 Ethernet study group that was investigating next generation digital homes. The work was moved over to an 802.1 AVB task group because most of the work needed to be done on the architectural and upper protocol layer. The goal of the group was to create a standard that could guarantee Quality of Service (QOS) for time critical services. The AVB standard has since then attracted interest not only from the consumer market but also from the automotive industry [27] [28] [31] [33] [35].

There are three specifications that Ethernet AVB is based on

- IEEE 802.1as, provides precise timing and accurate synchronization for streams.
- IEEE 802.1Qat, stream reservation protocol that provides support for the receiving node applications to request a reserved bandwidth path in the network from sending node to receiving node.
- IEEE 802.1Qav, rules that will ensure the network latency for a stream in the network and guarantees latency for highest traffic class.

There is also a fourth standard IEE 802.1BA that has the purpose of specifying default configurations and profiles to aid manufacturers creating AVB compatible products.

3.3.1 Supported Traffic

Ethernet AVB supports rate constrained traffic using the IEEE 802.1Qat and IEEE 802.1Qav standards. Real-time traffic is divided into class A and class B. Best effort traffic is also supported. Ethernet AVB uses the IEEE 802.1Q standard that adds VLAN tagging support. It includes a 3-bit priority field that indicate frame priority with values ranging from 0(best effort) to 7(highest).

3.3.2 IEEE 802.1as Time Synchronization

To synchronize an AVB stream in the network the devices will from time to time exchange timing information. The information allows the devices to synchronize their time base reference clocks with each other. It is derived from the IEEE 1588 standard and uses UDP over IP and the time base reference is derived from a high frequency 8 kHz clock source [27].

Devices in the network that supports AVB create a timing domain and within the domain a single device is selected Grand Master Clock. The master timing signal is sent

to all slaves in the domain so all the slaves are synchronized with the master clock. The Grand Master Clock can automatically be selected or manually configured. When AVB capable devices are physically connected to the switch they will start to send capability messages to each other. If they support IEEE 802.1as they will start to exchange synchronization messages with each other.

The Precision Time Protocol (PTP) from the IEEE 1588 standard is used to synchronize the master and slaves. The synchronization is a two step process and begins with the master sending Offset messages to the slaves. The offset message contains the master clock time and the offset time is calculated and corrected by the slave [30] as depicted by Figure 26.

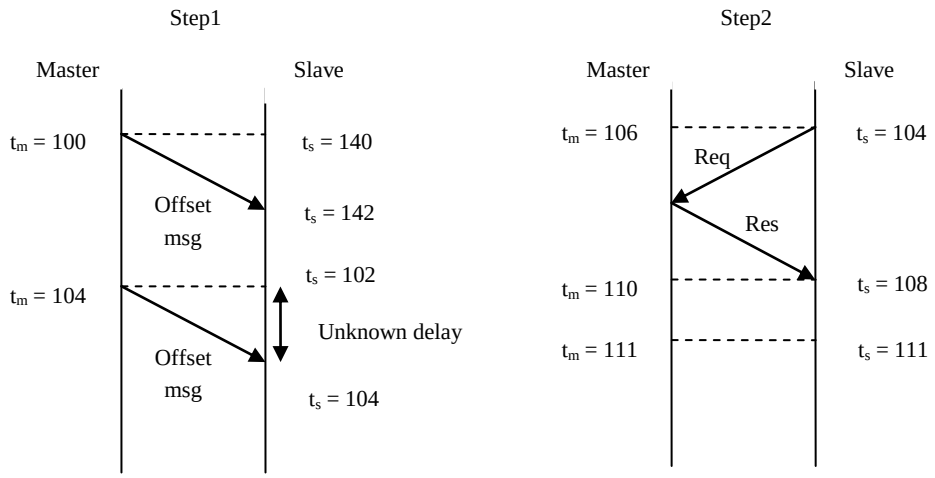


Figure 26. Two step PTP Master Slave Synchronization

At time t_m = 100 the master sends an offset message to the slave (the slave clock at this time instant is 140). When the message is received at t_s = 142 the slave calculates an offset based on the master time stamp carried in the message. The local clock on the slave is adjusted. When the next offset message is sent the slave can determine that the offset is zero. The master and slave clocks are now offset synchronized but not globally synchronized because the propagation delay is currently unknown.

The second step calculates the line delay and synchronizes the clocks globally. The algorithm is of request response type. It begins with the slave sending a delay request. When the request is received the master immediately responds. When the response message is received by the slave it calculates the line delay by subtracting the current time stamp with the previous and divides by two. The assumption here is that the line delay is evenly distributed between master and slave.

3.3.3 IEEE 802.1Qat Stream Reservation

Streams in Ethernet AVB are priority tagged and devices send frames based on the priority class and the QOS parameters when the stream is created. Talkers declare streams by specifying the stream class. There are two types of stream classes, A and B. The bandwidth needed for the stream is specified with a maximum packet size and the interval to send packets. Reservation of network bandwidth and buffers are done with a protocol called Stream Reservation Protocol (SRP). It is conducted in two steps called registration and reservation. A listener (devices receiving a stream) sends a registration message to the talker. The registration message is propagated through the switches to the talker and each switch that is passed makes an entry in its database so it can forward the reservation message sent by the talker to the listener. If there are other listeners interested in the same stream it might not have to propagate the registration message the talker. If the registration message passes a switch that is already forwarding the stream the switch can duplicate the stream out of the port connected to the new listener [27].

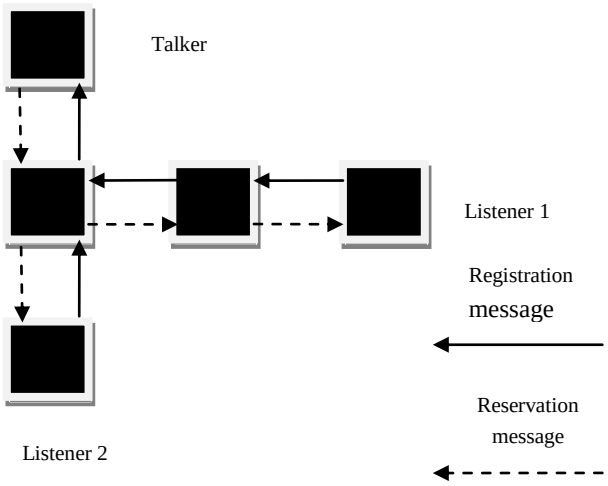


Figure 27. Talker and listener registration and reservation

In the example seen in Figure 27 Listener 1 sends a registration message through two switches that forwards the message to the talker. The talker sends a reservation message that reserves bandwidth between the talker and listener. Listener 2 sends a registration message to the first switch. The switch is already forwarding the stream that listener 2 is interested in so it duplicates the stream and sends it out of the port listener 2 is connected to. The assumption here is that there is enough bandwidth available to be reserved. If one of the switches along the way does not have enough bandwidth a negative response is generated and sent to the listener that requested the stream.

For the listeners to know what streams are available all the talkers advertise their stream by broadcasting the stream information. At each switch the worst case latency is recalculated so the listeners can use it to do accurate synchronization.

3.3.4 IEEE 802.1Qav Queuing and Forwarding

The stream classes A and B are mapped to two priority levels defined in IEEE 802.1Q. The traffic shaping defined in the IEEE 802.Qav uses credit based shaping. The traffic shaping creates a low upper limit on the size of the output buffers for the switches. This creates a bounded delay for the streams in an AVB network and eliminates network congestion [29].

Credit based shaping is similar to a token bucket algorithm. Credits increases as long as there are packets in the queue and when packets are transmitted credits are withdrawn. If the queue becomes empty the credits are cleared. The rate at which credits are incremented is based on the amount of bandwidth that is allocated to a specific stream.

The credit based shaping is implemented for the AVB streams and for each traffic class queue. For each stream queue the credit flow is based on the configured bandwidth limit. The rate of credit flow for each traffic class is based on the sum of all bandwidth limits for each stream associated with the specific traffic class.

3.3.5 AVB Switch

Best effort traffic uses lower priority levels than the traffic class A and B. In the specification it is recommended to only reserve up to 75 % of the bandwidth available to the AVB traffic. In each switch the queuing and forwarding specification segregates traffic into time critical and non-time critical packets. The time cycle is based on the 8 kHz clock source specified in IEE 802.1as. Traffic is scheduled on a 125 µs cycle for class A traffic and 250 µs for class B traffic. Time critical packets are transmitted first followed by the non-critical packets as long as it is not going to delay the start of the next time slot as depicted in Figure 28.

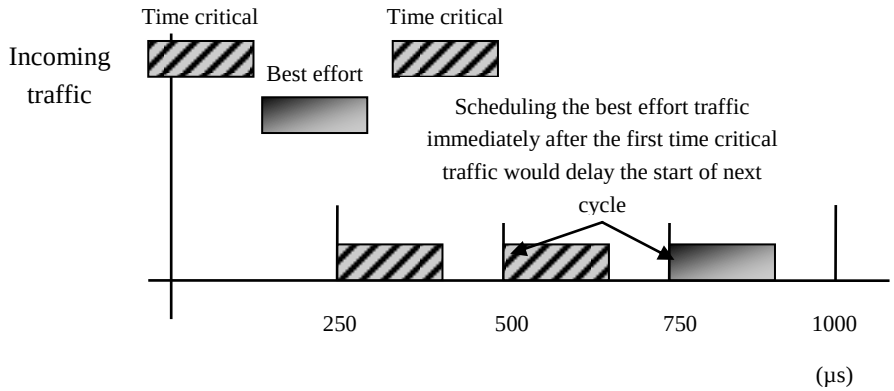


Figure 28. Packet pacing in Ethernet AVB switch

3.3.6 AVB Frame Format

Ethernet AVB frame is encapsulated in a standard 802.3 Ethernet frame with priority tagging. The priority tagging is used to distinguish between class A, class B and best effort traffic. The payload contains the AVB header which consists of the stream id and other implementation specific parameters that depends on the type of stream data. A 32-bit time stamp is included before the AVB stream data as depicted in Figure 29.

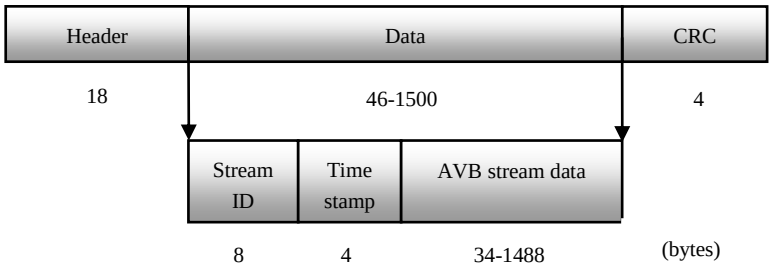


Figure 29. AVB frame format

3.3.7 Current Status

Toyota, NEC Engineering and Broadcom have released two papers [30] and [33]. It includes an example of a converged backbone using Ethernet AVB. They highlight automotive requirements for the backbone which includes

- Fail-safe systems and quick recovery
- Acknowledgement and retry
- Ultra-low latency for critical control applications

It is suggested that for lower class data developers can use TCP/IP above the AVB protocol layer for acknowledgement and retry. If TCP/IP is too costly they suggest using a simple confirmation procedure. The receiver node returns an acknowledge frame for each frame sent from the sender node. It is applicable to protocols whose messages fit in a single Ethernet frame due to no frame reordering or reassembly.

Automotive systems shown in [33] propose the use of a higher layer protocol IEEE 1722 that takes advantage of the features of AVB. It is currently necessary to define frames for acknowledgement and retry and for encapsulating packets from other communication buses such as CAN. As of today there are some signs of a start to automotive support in IEEE 1722 for a CAN and FlexRay gateway protocol [8] (See [32] for more information about IEEE 1722).

An article published in June 2011 [36] describes a 360-degree view system with Ethernet. BMW together with Freescale produced a microcontroller that is used as a gateway in a 360-degree camera system. The microcontroller has partial support for the Ethernet AVB standard.

3.4 Summary of Analyzed Protocols

The three analyzed protocols can be categorized into two domains

- Time-Triggered Communication
- Rate constrained Communication

Rate constrained communication is supported by all of the solutions (AFDX, TTEthernet and Ethernet AVB). The traffic shaping in Ethernet AVB is not based on a periodic shaper but a credit based shaper.

TTEthernet advantage is that it supports time triggered, rate constrained and best effort traffic. The time triggered communication allows fast control loops with minimal latency and jitter because time triggered messages are sent over the network at predefined times. A disadvantage with the time triggered communication is that it is less flexible if changes are to be made to the nodes. If a node changes when messages are sent the global time schedule uploaded to the switch needs to be changed. TTEthernet does not specify a specific header for the time triggered traffic because it is sent in special messages called protocol control frames. As a result you have less overhead for time triggered traffic compared to the rate constrained AFDX protocol that uses IP and UDP as headers.

A disadvantage for TTEthernet is that it requires a custom switch to support the time triggered communication model and is currently only available from TTTech but it is currently as of 2011 undergoing standardization and will be known as a SAE 6802. When the standardization is finalized it is most likely that more manufacturers will produce TTEthernet compliant switches and nodes. Future x-by-wire applications may require high sampling rates above one KHz and strict deterministic behavior and for such applications the time triggered solution is a good choice. TTEthernet has been compared to FlexRay and the outcome was that it is a suitable replacement for an in-vehicle network [24].

Both TTEthernet and AFDX support dual redundancy. The fault tolerant suggestion for Ethernet AVB is a rapid spanning tree protocol which is more complex than using two

of everything. The latest suggestion for automotive adaptations for Ethernet AVB is to use faster timers that can detected broken links and do recovery in less than 70 ms [30].

The AFDX rate constrained communication guarantees an upper bound on the transmission latency. Bandwidth is predefined for the messages sent by all applications but in comparison to time triggered communication it is not sent on a synchronized time base. Rate constrained communication could be used as a high bandwidth Ethernet backbone carrying message from sub buses such as CAN, LIN et cetera.

AFDX supports the rate constrained communication model and it is possible to do evaluation and experiments using a low cost managed switch because it exploits the MAC destination address in standard Ethernet as a way to route messages. Both AFDX and TTEthernet are statically configured at design time and that is an advantage when it is used as an in vehicle Ethernet backbone as they are normally closed systems. A comparison between CAN, AFDX and FlexRay for ABS systems showed that AFDX achieved identical performance compared to a FlexRay solution [19].

Ethernet AVB is developed by IEEE and has a potentially large customer base. It is primarily marketed to the audio and video consumer/industry market however the automotive industry has shown interest in the standard. The rate constrained model in Ethernet AVB requires support in all switches along the route to support the dynamic requests of streams and reserve bandwidth. Each switch knows about the streams that flow through the switch. The request for a stream from a listener does not need to propagate all the way to the sender if the stream is already transmitted through a switch along the route. That might not be needed for an Ethernet backbone but can be beneficial for an end user entertainment system.

Currently a subset of the AVB standard has seen use in a BMW camera system utilizing the IEEE 802.1as which is used as a way to accurately synchronize the clocks [36].

The AFDX rate constrained traffic model is the most suitable protocol for Scania adaptation if a low cost prototype should be implemented. Support for the virtual link routing is possible with a smart switch.

The development process at Scania uses an iterative approach and would benefit from adding new messages without large changes in the configuration. In that sense Ethernet AVB would be the most suitable protocol due to the support of dynamically allocating streams. On the other hand both Ethernet AVB and TTEthernet require special switch support. If time triggered communication is wanted in the future a switch based on the TTEthernet technology is easily deployed because it already supports the AFDX standard. If care is taken at design time by allocating enough virtual links the AFDX protocol can support introduction of new messages without large changes in the configuration.

4 Design and Implementation

This chapter suggests an Ethernet backbone structure and describes a design and implementation of a network stack using the rate constrained AFDX protocol standard.

4.1 Suggested Ethernet Backbone

The suggested network architecture uses an Ethernet backbone to offload the CAN buses. The CAN buses with high bus load is divided into sub buses and connected to the high bandwidth Ethernet backbone as depicted in Figure 30.

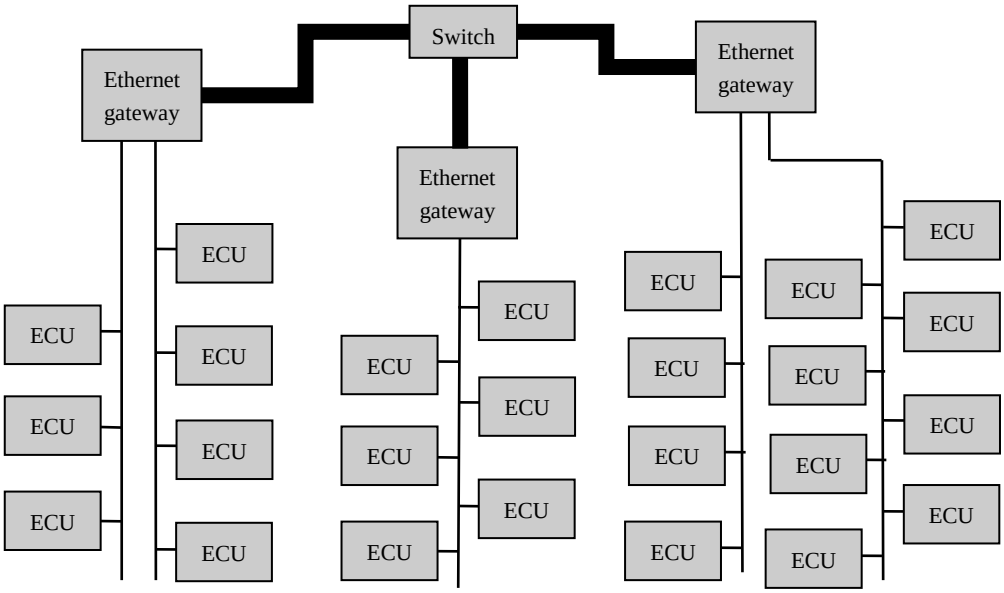


Figure 30. Suggested Ethernet backbone

New applications requiring high bandwidth is connected to the switch. It is also possible to communicate with ECU's on the lower bandwidth CAN buses through the Ethernet gateways.

4.2 The Software Stack

The design and implementation is not assumed to be used in any sort of critical system but merely as a demonstration how J1939 messages can be transported over a rate constrained Ethernet backbone model. The design is based on the documentation for the AFDX protocol and it implements a subset of the protocol. Supported are the periodic scheduler and the concept of virtual links as a way to partition the available bandwidth in the cable.

The communication ports implemented are queuing ports. A transmitter using a queuing port appends new messages in FIFO order and messages are transmitted at the time instant the virtual link is scheduled. The receiver retrieves messages from the queue. The implementation creates correct UDP/IP packets and calculates the checksum but does not support the packet segmentation and reassembly. If an application tries to write a message that is bigger than the configured virtual link Lmax parameter the message will be truncated.

4.3 Platform

The user mode software stack currently builds on Windows, and Linux (Ubuntu and Embedded Linux). It is developed in C++ using standard C/C++ libraries. It should be easy to port to all platforms that support C/C++.

4.4 Tools and Libraries

The software has been developed primarily in Ubuntu (kernel version 2.6.38-8) using a simple text editor. The Ubuntu Linux distribution ran inside a virtual machine on top of a Windows XP 32 bit host.

The frames created differ from standard Ethernet packets because the destination MAC-address is used to identify virtual links. Therefore data link layer access is needed. A network library that supports data link access has been used to develop the software stack. The network library is called libpcap [37]. The software stack uses POSIX threads for multithreading and more information about pthreads can be found at [38].

The motive using Linux as development platform was because it was intended to try and run the experiments using existent hardware (PowerPC architecture running an Embedded Linux distribution). During the development of the software stack it was detected that the embedded Linux distribution had been compiled without raw socket support and was configured in half duplex mode. Without raw socket support the

software stack cannot access the data link layer to create the specific frames that is used in the protocol.

A decision was made to port the stack to Windows using the Windows port of libpcap called winpcap [39]. A port of pthreads for windows [40] was used to replace POSIX threads. On Windows the Microsoft Visual C++ Studio 2010 Express development environment was used. Later a custom build for the embedded platform was produced but due to lack of time it was decided to run the experiments using the windows port.

4.5 Design

A simplified UML diagram shows the design of the software stack as depicted in Figure 31.

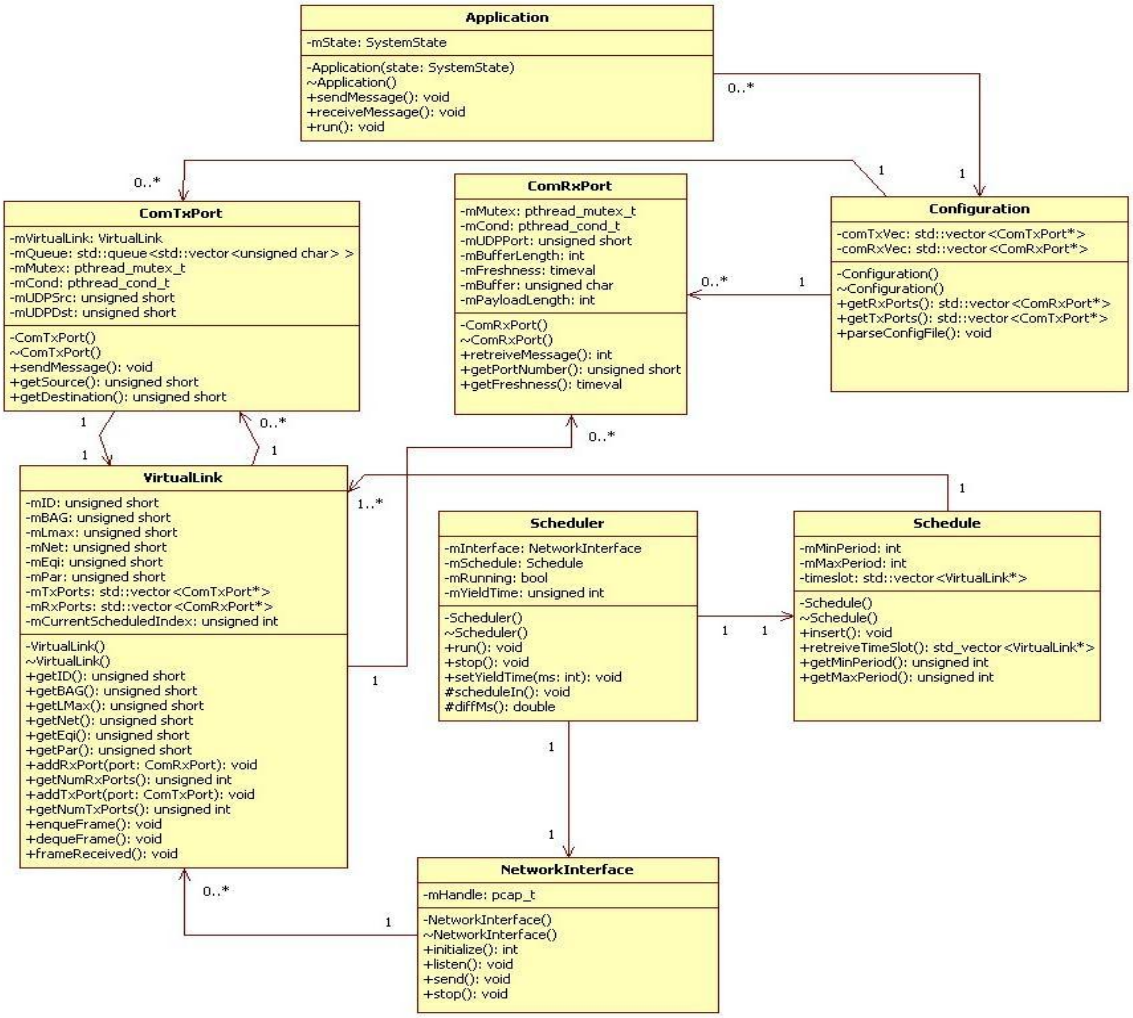


Figure 31. UML diagram of the software stack

The application class is used to send and receive messages from the network stack. It has a reference to a configuration class that holds the current transmit and receive ports

in the system. It is possible for the applications to send and receive using blocking or asynchronous I/O. In blocking mode the sendMessage() method returns after the scheduler has dispatched the message. In asynchronous mode it returns immediately after putting the message in the message queue. In blocking mode the receiveMessage() method blocks until the underlying virtual link has received a message intended for the particular receive port. It is also possible to specify a timeout value. In asynchronous mode it polls the receive port if a new message has been received and returns immediately. The applications run as separate threads.

The Configuration class has the responsibility to parse the specified configuration file at system startup. The configuration file contains a list of the virtual links, transmit and receive ports and how they are connected to each other. The parseConfigFile() method takes a filename as argument and parses the file. The application class can then use the Configuration class to retrieve the transmit and receive ports using getRxPorts() and getTxPorts() methods.

The ComTxPort class represents a transmit port in the AFDX standard. It has a message queue that holds the message awaiting transmission by the scheduler. Since the message queue is used by both the applications in the system and by the scheduler access to the queue is protected by a mutex. The condition variable is used by the underlying virtual link to signal when message is transmitted by the scheduler. It is only signaled if the call to the sendMessage() method uses blocking mode. The ComTxPort has an UDP source and destination port number that is mapped to the UDP protocol source and destination port number when transmitting the message.

ComRxPort represents a receive port in the AFDX standard. The buffer is configured to hold a specific number of messages. The mutex is used to protect access to the buffer since it is used by the applications receiving messages from the receive port and the underlying virtual link that writes new messages to the buffer. The condition variable is used to signal the receive port when the virtual link has written a new message to the buffer. It is only signaled if the application using the receive port has made the call to receiveMessage() in blocking mode. The freshness value indicates when the last message in the buffer was received.

The VirtualLink class implements the concept of a virtual link according to the AFDX standard. The two most important parameters are called BAG and Lmax. BAG regulate how often the dequeFrame() method will be called by the scheduler. Lmax regulate the maximum packet size that a single message can occupy. The two parameters together restrict the maximum bandwidth used by the virtual link. The virtual link removes messages from each connected transmit port in round robin order. If the current scheduled transmit port is empty the virtual link moves to the first non empty transmit port. If they are all empty nothing is transmitted.

The Schedule class contains the schedule that has timeslots divided into 128 different slots. The schedule uses 128 timeslots since the AFDX standard defines the range of BAG values as a power of two ranging from 1 to 128 ms. Virtual links are inserted into the schedule based on the BAG value for each link. The scheduler optimizes the schedule by adjusting the phase of virtual links with the same BAG value. For example if two virtual links with the same BAG value of 2 ms are to be scheduled the first link is inserted into slot 0, 2, 4, 6 et cetera. The second link is adjusted in phase to reduce serialization jitter of the two links by inserting it in time slot 1, 3,5,7 et cetera. It is possible for each timeslot to have multiple virtual links and if they do the virtual links is serialized at the cost of jitter.

The Scheduler uses the schedule and runs in a separate thread. The Scheduler uses the method retreiveTimeSlot() from the Schedule class to retrieve the current timeslot to be scheduled. It then calls the method DequeFrame on each virtual link in the timeslot. If a message is retrieved it is sent to the network interface. It is possible for the scheduler to yield until the next schedule time. The accuracy and granularity of the yield time depends on the underlying operative system. The NetworkInterface class uses pcap to send packets to the network card. See Appendix B for sequence diagrams.

4.6 Transmission of J1939 Messages

The messages periods used in the experiments with the implemented prototype was selected from a database. The database contains messages sent over the red CAN bus. A subset of the messages was selected with varying periods. The real message names of M1-M20 are concealed but they are real J1939 messages used by Scania today. Two experiments were performed with the prototype.

The first experiment adds J1939 message frequencies and dimensions the virtual links to carry messages based on their total frequency. The second experiment uses a single virtual link and encapsulates multiple messages in a single Ethernet packet.

The application layer has no support to do synchronized sends with the virtual link scheduler. As a result special support to assemble multiple J1939 messages into a single Ethernet packet was therefore added in the stack. The virtual link will retrieve all the messages in the transmit queue port and assemble it into an Ethernet packet when the virtual link is scheduled.

The goal is to compare the two experiments how they differ in bandwidth utilization, overhead for each Ethernet message and worst case delay. J1939 messages were modeled with timers interrupting at the frequency of each message. The messages were injected into the transmitting node and time stamped. At the receiving node the measured results are written to a file.

4.6.1 First Experiment Using Frequency Accumulation

The first experiment calculates virtual link BAG values by adding message frequencies. See section 3.1.3 for an example. VL_1 with a BAG value of 2 ms is calculated from adding the frequencies for three messages with a period of 10 ms, VL_2 from the four messages with a period of 20 ms, VL_3 from the the three messages with a period of 50 ms and VL_4 from the messages with a period of 100, 1000 and 5000 ms. The CAN message structure used has a 4 byte identifier and 8 bytes of data. The 4 byte identifier is able to hold the 29 bit identifier. Consequently the Ethernet packet size is

$$14(Ethernet\ Header) + 28(UDP/IP) + 12(Payload) + 5(SEQ + CRC) = 59\ bytes$$

Since the minimum Ethernet packet size is 64 bytes, 5 bytes of padding is used. The message to virtual link mapping is depicted in Figure 32.

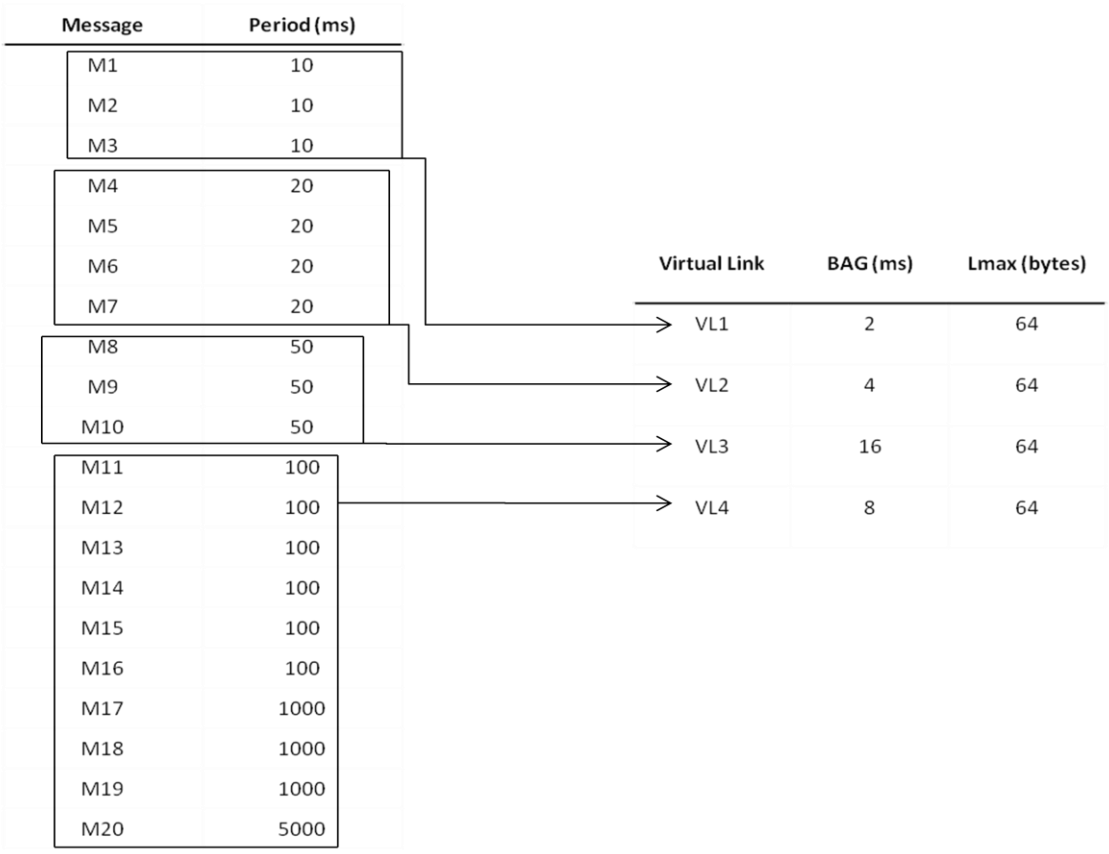


Figure 32. Message set mapping in first experiment

A queuing port is used for each message so VL_1 has three ports connected to it, VL_2 four, VL_3 three and VL_4 ten. The configuration file the sending node uses in the experiment is depicted in Figure 33.

```
[LINKS]  // link id, lmax, bag, network, equipment, partition
4
1000 64 2 1 1 1
1001 64 4 2 2 2
1002 64 16 3 3 3
1003 64 8 4 4 4
[TXPORTS]  // port id, link ref, source port, destination port,
20
0 1000 50000 50100
1 1000 50001 50101
2 1000 50002 50102
3 1001 50003 50103
4 1001 50004 50104
5 1001 50005 50105
6 1001 50006 50106
7 1002 50007 50107
8 1002 50008 50108
9 1002 50009 50109
10 1003 50010 50110
11 1003 50011 50111
12 1003 50012 50112
13 1003 50013 50113
14 1003 15014 50114
15 1003 15015 50115
16 1003 15016 50116
17 1003 15017 50117
18 1003 15018 50118
19 1003 15019 50119
[RXPORTS]  // port id, link ref, destination port
0
```

Figure 33. Configuration file for the first experiment

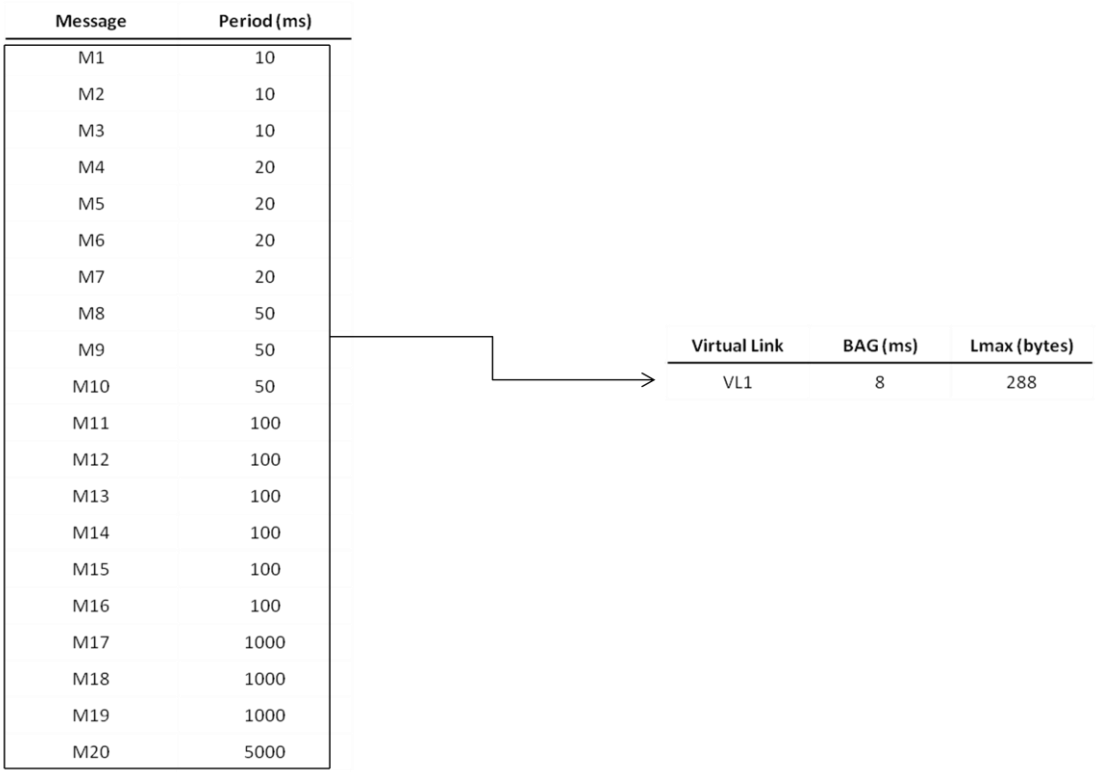
4.6.2 Second Experiment Using Message Encapsulation

The second experiment packs multiple messages into a single Ethernet packet. When packing multiple J1939 messages into one Ethernet packet the Ethernet payload field need at least a header to identify the number of J1939 messages that is sent in the Ethernet packet. It is assumed each message has a fixed size. The BAG value for each virtual link carrying multiple messages in a single packet needs to be smaller than the message with the smallest period in the set.

If all the messages in the set are sent on a single virtual link the BAG value needs to be set to less than 10 ms (the smallest period for a single message in the set). The Lmax parameter is set to the worst case that could happen when all the messages have been received between two scheduled transmissions of the virtual link. The allocated bandwidth for the virtual link has to be large enough to hold all the messages in a single Ethernet packet. A small header is used to indicate the number of messages packed in the Ethernet packet. The J1939 message structure is 12 bytes and the selected message set contains 20 messages so the Lmax parameter is set to

$$14(Ethernet\ Header) + 28\ (UDP/IP) + 1(NrOfMsgs) + 12 * 20(Payload) + 5(SEQ\ \&\ CRC) = 288\ bytes$$

The message to virtual link mapping is depicted in Figure 34.



Message	Period (ms)
M1	10
M2	10
M3	10
M4	20
M5	20
M6	20
M7	20
M8	50
M9	50
M10	50
M11	100
M12	100
M13	100
M14	100
M15	100
M16	100
M17	1000
M18	1000
M19	1000
M20	5000

Virtual Link	BAG (ms)	Lmax (bytes)
VL1	8	288

Figure 34. Message set mapping in second experiment

The configuration file used by the sending node in the second experiment is depicted in Figure 35. A single port is connected to the virtual link.

```
[LINKS]  // link id, lmax, bag, network, equipment, partition
1
1000 448 8 1 1 1
[TXPORTS]  // port id, link ref, source port, destination port,
1
0 1000 50000 50100
[RXPORTS]  // port id, link ref, destination port
0
```

Figure 35. Configuration file for the second experiment

5 Results of Experiments

This chapter presents the results from the experiments.

For time measurement the query performance counter was used. The experiments were performed on two machines with a dual core 3 GHz processor running Windows XP on a 100 Mbit/s network. The timers on the two nodes were synchronized each second with the master node transmitting the master clock to the client node. After the reception of the clock value the client node measures the transmission delay by sending a request to the master. The master immediately replies and when the client node receives the reply it calculates the delay by estimating the delay to be equally distributed between the sending of the request and receiving the reply. At most for all the experiments a maximum clock drift of 100 µs was recorded. This is apparent in the results for the measured minimum delay which in some cases are measured as low as 0 ms which is impossible. See Appendix A for a table with delay values for each message for both of the experiments.

The first experiment configured with four virtual links and a transmit port for each message was run three times and each run lasted for 20 seconds. A total of 35883 packets sent and all messages were received earlier than their deadlines (equal to the message period). The results are depicted in Figure 36 using a stacked histogram showing the frequency distribution of packets for each virtual link with a bin size of 2 milliseconds.

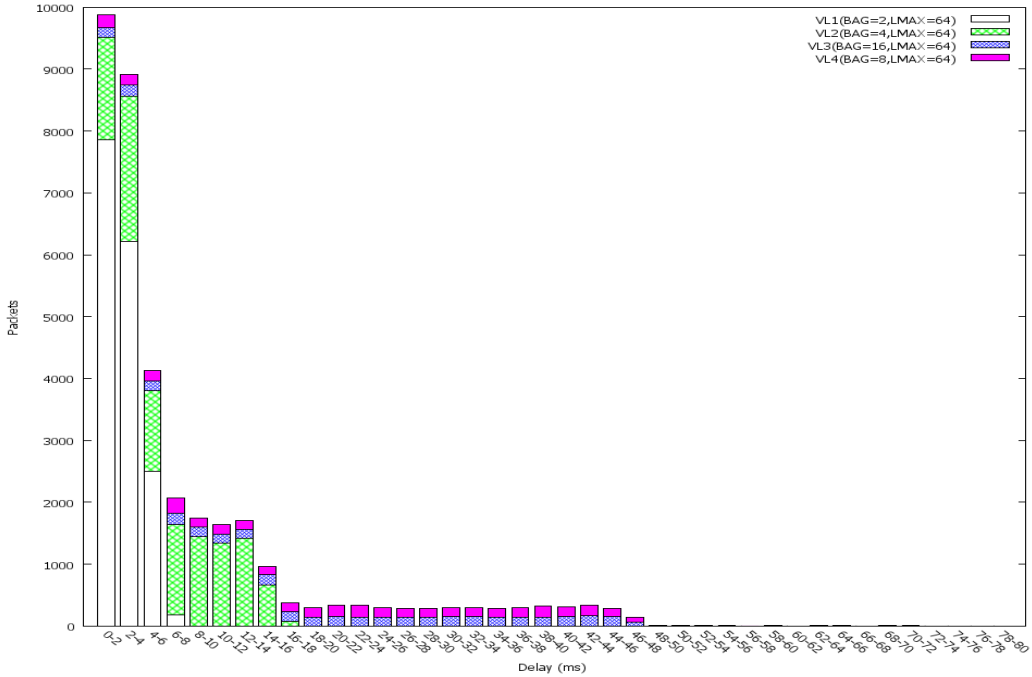


Figure 36. Results for the first experiment

The second experiment configured with a single link and a single port was run three times and each run lasted for 20 seconds. A total of 35882 packets sent and all messages were received earlier than their deadlines. The results are depicted in Figure 37 using a stacked histogram showing the frequency distribution of packets for each virtual link with a bin size of 2 milliseconds.

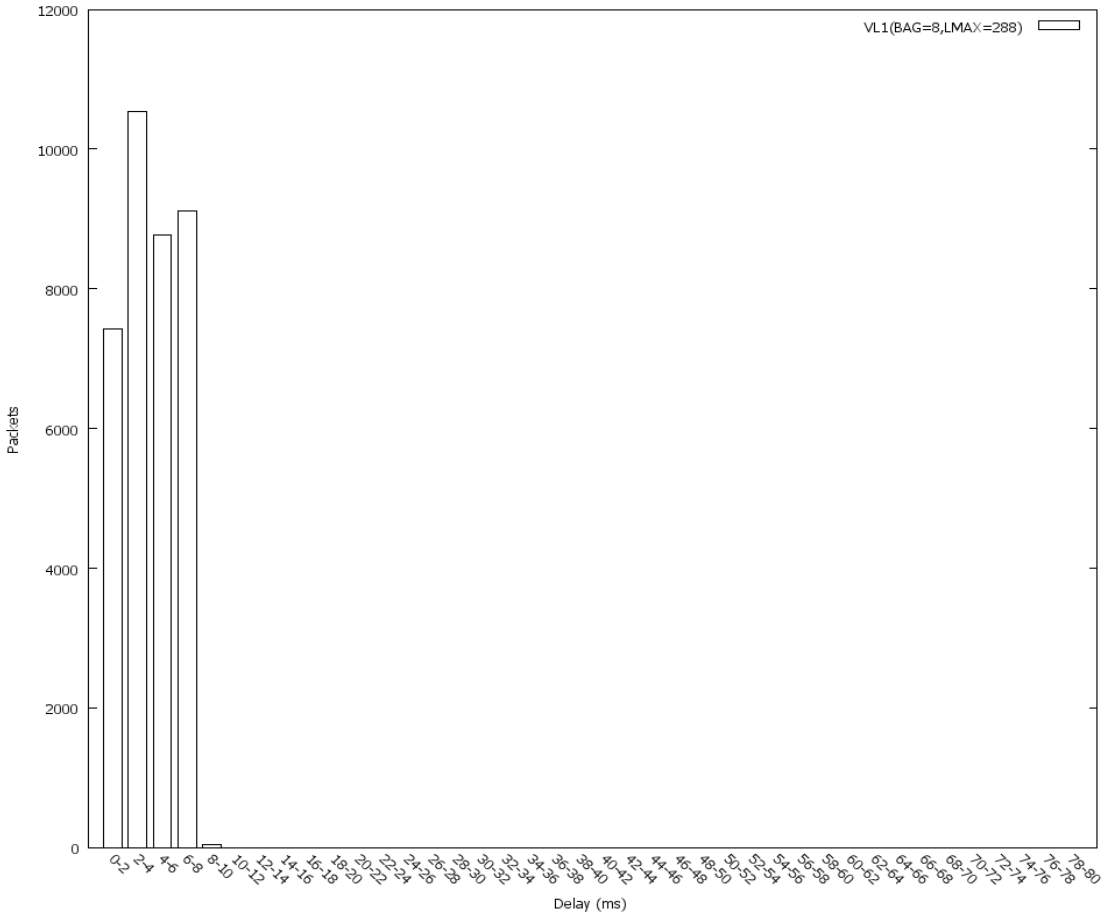


Figure 37 Results for the second experiment

The total amount of bandwidth reserved for all the virtual links in the first experiment is

$$\frac{1000}{2}(VL1) * 64 + \frac{1000}{4}(VL2) * 64 + \frac{1000}{16}(VL3) * 64 + \frac{1000}{8}(VL4) * 64$$
$$= 60000\ bytes$$

For a 100 Mbit/s network the reserved bandwidth in a single segment is

$$\frac{60000}{10^8/8} = \frac{60000}{12500000} = 0.0048 = 0.48\ \%$$

The frame overhead for each message in the first experiment is

$$\frac{52}{64} = 81.25\%$$

Most of the packets in VL_1 is sent and received within 2 milliseconds. The distribution of packets for VL_2, VL_3 and VL_4 are in general equal.

The total amount of bandwidth reserved for the virtual link in the second experiment is

$$\frac{1000}{8} * 288 = 36000\ bytes$$

For a 100 Mbit/s network the reserved bandwidth in a single segment is

$$\frac{36000}{10^8/8} = \frac{36000}{12500000} = 0.0288 \approx 0.29\ \%$$

For the second experiment the average number of messages encapsulated in a single Ethernet transmission was also measured. The result showed that on average five messages were transmitted. For a virtual link with the Lmax parameter set to 288 bytes only

$$288 - 15 * 12 = 108\ bytes$$

of the virtual link capacity is used.

The second experiment has almost the same overhead (one byte difference due to the extra one byte header) for the worst case if a single message is transmitted. On average when approximately 5 packets are sent the overhead is

$$\frac{48}{108} \approx 0.444\ \approx 44\%$$

In the best case if all 20 messages are pending transmission

$$\frac{48}{288} \approx 0.166 \approx 16.6\%$$

Since all the messages are sent in a single virtual link the worst case latencies are similar for all messages.

Even if all messages for the two experiments were received before their deadline (deadline equal to message period) it should be noted that the experiments was run on a non real-time operating system. The virtual link scheduler in the experiments tries to use as little processor time as possible and yields the remaining time until the next scheduling time. Due to limitations in sleep granularity and context switches some messages carried by VL_1 and VL_2 in the first experiment exceed the theoretical maximum delay which is

$$3\ (messages) * 2\ ms\ (scheduling\ period) = 6\ ms\ (VL1)$$

$$4\ (messages) * 4\ ms(scheduling\ period) = 16\ ms\ (VL2)$$

Furthermore, the first experiment shows that it is difficult to produce a perfect schedule when accumulating multiple message frequencies to be carried by a single virtual link. There is reserve capacity in the first experiment and it is possible to send more messages in each virtual link without changing the scheduling periods. It would easier if the messages carried by each virtual link had a frequency that fits the power of two virtual link scheduling periods.

In the second experiment all messages fit in a single Ethernet message. A few packets violate the maximum scheduling period of 8 milliseconds. A way to verify this was made by measuring the time from message injection by an application to message dispatch by the virtual link scheduler. It showed that in all cases when the maximum delay was recorded for the messages, the dispatch time for the virtual link scheduler had been delayed due to thread preemption.

It is only a few packets that exceeded the theoretical maximum message delay and the average delay for all messages in both experiments is below the theoretical maximum delay for all virtual links

5.1 Summary

The first experiment has higher frame overhead due to the relatively large UDP/IP header and only sending one J1939 message for each Ethernet packet. The most important difference lies in the complexity and how much the allocated bandwidth grows when adding messages to the virtual link.

To visualize the main difference between the two experiments picture a single virtual link with a scheduling period of 16 milliseconds and a maximum frame size of 64 bytes. Messages with a period of 16 milliseconds are added to the virtual link. With a single message to be transmitted the allocated bandwidth for both experiments would be equal. If an additional message is added, the scheduling period with frequency accumulation needs to be changed to 8 milliseconds for the virtual link, effectively doubling the allocated bandwidth. With multiple messages in a single packet only the maximum frame size needs to be changed to fit two messages. As depicted in Figure 38 the complexity for frequency accumulation resembles a staircase. The multiple messages have slow linear growth.

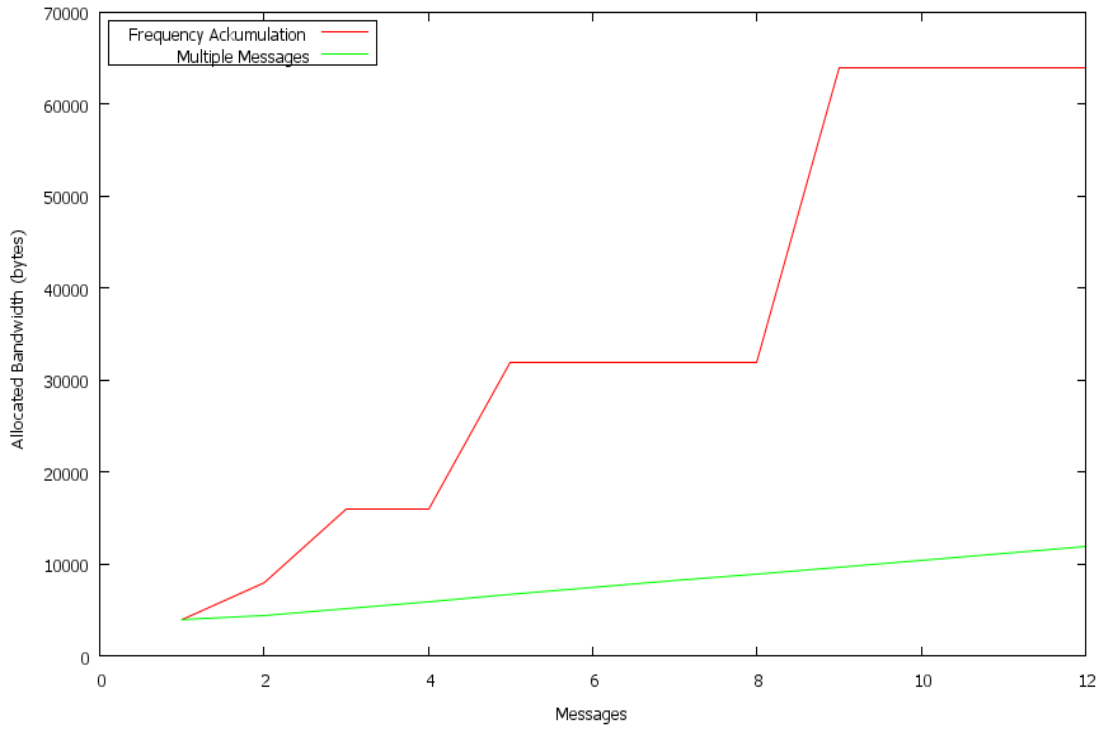


Figure 38. Comparison between frequency accumulation and multiple messages

Consequently the second experiment is more efficient carrying J1939 messages even though it has low average utilization. The first experiment is less efficient due to the complexity difference and large overhead.

6 Discussion

This chapter discusses how to provide support for incremental updates, software and message compatibility, reducing overhead and improvements that can be made to the prototype developed.

6.1 Incremental Updates

Incremental updates are possible with the proposed protocol if care is taken at design and planning stage. By allocating reserve capacity in the virtual links it is possible to add new messages sent from an ECU without updating the virtual link schedules in the transmitting/receiving ECU's and switch.

6.2 Software and Message Compatibility

One way of providing backward compatibility for messages carried over an Ethernet solution is to use some form of serialization format. Protocol buffers are Google's approach to provide a serialization format and it is described in a similar way as XML. The messages are defined in .proto files.

```
message ether_message{
      required int32 id = 1;
      optional int32 a = 2;
      optional int32 b = 3;
      optional string description = 4;
}
```

Messages have one or more uniquely numbered fields, each field has a name and a value type. There are three types of fields required, optional and repeated. A reader expects the required field to be in the message otherwise it is deemed incomplete. The optional field is not required and the reader parses the message correctly even if it is not supplied. The repeated field can be repeated any number of times including zero. The .proto file is compiled to C++ code and can be used by application developers in the following way

```
ether_message msg;
msg.set_id(1234);
msg.set_a(5);
msg.set_b(6);
msg.set_description(”ether_message”);
msg.serializeToStream(&output);
```

To use it with the rate constrained software stack the serialized stream is then sent to a transmit port. If an existing message type no longer meets the requirement it can be extended by adding additional fields. Code created with the old format is still compatible with the new format apart from that it is ignoring the additional fields in the message. It is therefore possible for an old device running applications using the old format to communicate with newer applications using the new format. As a result old software in ECU’s are able to communicate using the old message format with newer ECU’s using the new message format. For more information about Google protocol buffers see [41].

6.3 Reducing Overhead

The AFDX protocol uses a UDP/IP header but a simple closed backbone with a single switch could use a smaller header which reduces the amount of overhead for each packet. The header may possibly be small enough so the network stack can differentiate between messages intended for different ports. Implementing such a design could be done using the MAC destination address and the priority field of an 802.1Q Ethernet frame to distinguish between time critical and best effort traffic in similar way as TTEthernet and Ethernet AVB. The time critical traffic could then use the smaller header. Another alternative is to use larger messages by converging functionality and sending more information in larger packets.

6.4 Improvements to the Prototype

An implementation of the sampling port type needs to be done. The scheduler for the virtual link can be used to trigger callbacks for the application layer. Applications would be scheduled at the same time instant as the virtual link and could send messages synchronized with the regulator.

The virtual link scheduler in the experiments tries to use as little processor time as possible and yields the remaining time until the next scheduling time. The Windows XP scheduler puts the network scheduler thread in a wait state when it yields. Due to

limitations in the sleep granularity and context switches the time it takes for the thread to wake up is nondeterministic. To get better results from the network scheduler the protocol stack should be implemented in a real-time operating system.

7 Conclusion

CAN is reaching its limits when it comes to bandwidth. In the future more bandwidth is needed and new features require more bandwidth. Ethernet is an interesting technology to use as a way to solve the problem.

First three Ethernet real-time protocols were studied. The three studied protocols were AFDX, TTEthernet and Ethernet AVB.

Thereafter, a prototype was designed and implemented. The prototype was based on the AFDX protocol because it is the most suitable protocol for Scania adaptation if a low cost prototype should be implemented. Support for the virtual link routing is possible with a standard smart switch. The other protocols require dedicated switch hardware.

The prototype was evaluated in two experiments. Both experiments transmit J1939 messages over a simulated Ethernet backbone. The first experiment uses frequency accumulation to parameterize the virtual links. The second experiment tries to pack multiple J1939 messages in a single Ethernet packet.

The results of the experiments were that the second experiment is the most efficient. The first experiment has higher frame overhead due to the relatively large UDP/IP header and only sending one J1939 message for every Ethernet packet. The most important difference lies in the complexity and how much the allocated bandwidth grows when adding messages to the virtual link.

The development process at Scania uses an iterative approach and would benefit from adding new messages without large changes in the configuration. In that sense Ethernet AVB would be the most suitable protocol due to the support of dynamically allocating streams. On the other hand both Ethernet AVB and TTEthernet require special switch support. If time triggered communication is wanted in the future a switch based on the TTEthernet technology is easily deployed because it already supports the AFDX standard. If care is taken at design time by allocating enough virtual links the AFDX protocol can support introduction of new messages without large changes in the configuration.

To improve performance the stack should be implemented using a real-time operating system and put in the driver layer. Moving the virtual link scheduler to a separate hardware implementation is even better although that is obviously a cost concern. It has been observed that in the current CAN network it is difficult to get an accurate estimation of the bus load. The benefit of a rate constrained Ethernet model is that the total amount of allocated capacity can be calculated offline. Another benefit is that if an application tries to push more data than allocated for by the virtual link it will not degrade the whole network but it is isolated to the virtual link.

Ethernet in a real-time vehicle network is a viable solution. With full duplex there is no access arbitration to the medium. The prototype implemented in this degree project uses a rate constrained traffic model and removes the remaining problem with uncertain buffer contention. As a result the prototype can be used a starting point for a future Ethernet backbone.

8 Future Work

This chapter presents the future work and an idea how the protocol and the Ethernet solution could be introduced in accordance with the release process used at Scania.

As this report is not covering the electrical layer and how the cabling should be done the future work should be focused on investigating cabling, electromagnetic compatibility, contacts and finding a suitable switch that support a programmable MAC-address table and preferably support for 802.1Q to be able to prioritize between different traffic classes.

The release process used at Scania presents a number of difficulties when introducing the proposed Ethernet solution. A change from a single coordinator to an Ethernet backbone overnight in a single release is not a feasible approach. Gradually implementing the Ethernet solution in accordance with the current release process is one feasible approach. A starting point could be the Coordinator that is used to connect the different CAN buses today.

In the first step an Ethernet port is added to the Coordinator. Support for the proposed Ethernet protocol is then implemented in the Coordinator. It is then possible in later stages to create new CAN or other low bandwidth buses using a gateway between the switch as depicted in Figure 39. Other high bandwidth applications are also possible to connect to the switch. An idea for the future is to investigate the feasibility and its implications to gradually move existing ECU's from the current red, green or yellow buses to the newly created gateways.

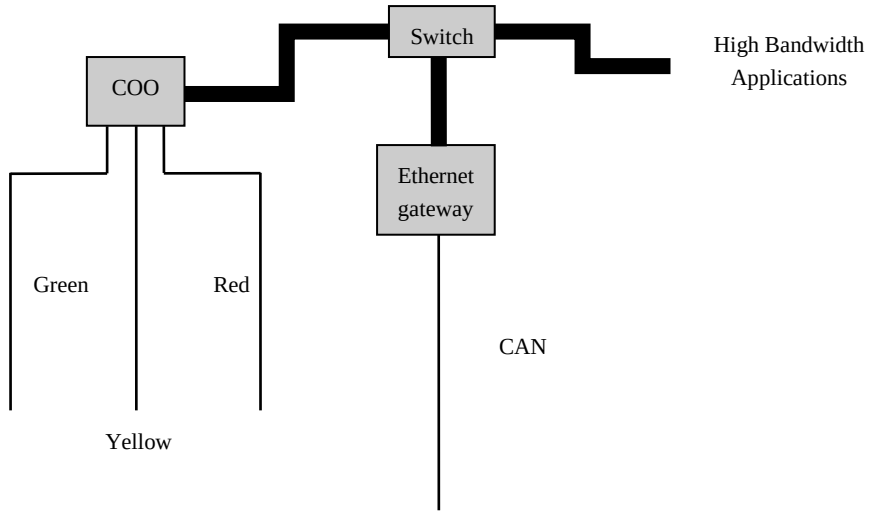


Figure 39. Using Coordinator as a starting point

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Appendix A Delay tables

Message	Period (ms)	Minimum delay(s)	Maximum delay(s)	Average delay(s)	Packets sent
M1	10	0.000015	0.009399	0.003727	5582
M2	10	0.000015	0.009384	0.001444	5584
M3	10	0.000816	0.008430	0.002460	5584
M4	20	0.000015	0.017632	0.005636	2927
M5	20	0.000015	0.017639	0.007820	2929
M6	20	0.000015	0.017639	0.007589	2932
M7	20	0.000023	0.019250	0.008016	2935
M8	50	0.000046	0.016754	0.007473	1186
M9	50	0.010834	0.032875	0.022813	1187
M10	50	0.002975	0.048004	0.038737	1189
M11	100	0.000053	0.074348	0.022688	601
M12	100	0.000046	0.077301	0.018578	603
M13	100	0.000046	0.064606	0.018296	605
M14	100	0.004913	0.072418	0.025909	607
M15	100	0.000053	0.055809	0.023944	609
M16	100	0.005997	0.063622	0.030900	610
M17	1000	0.000031	0.055809	0.014037	63
M18	1000	0.003937	0.063522	0.021552	66
M19	1000	0.000053	0.070374	0.025651	69
M20	5000	0.006981	0.078239	0.040363	15

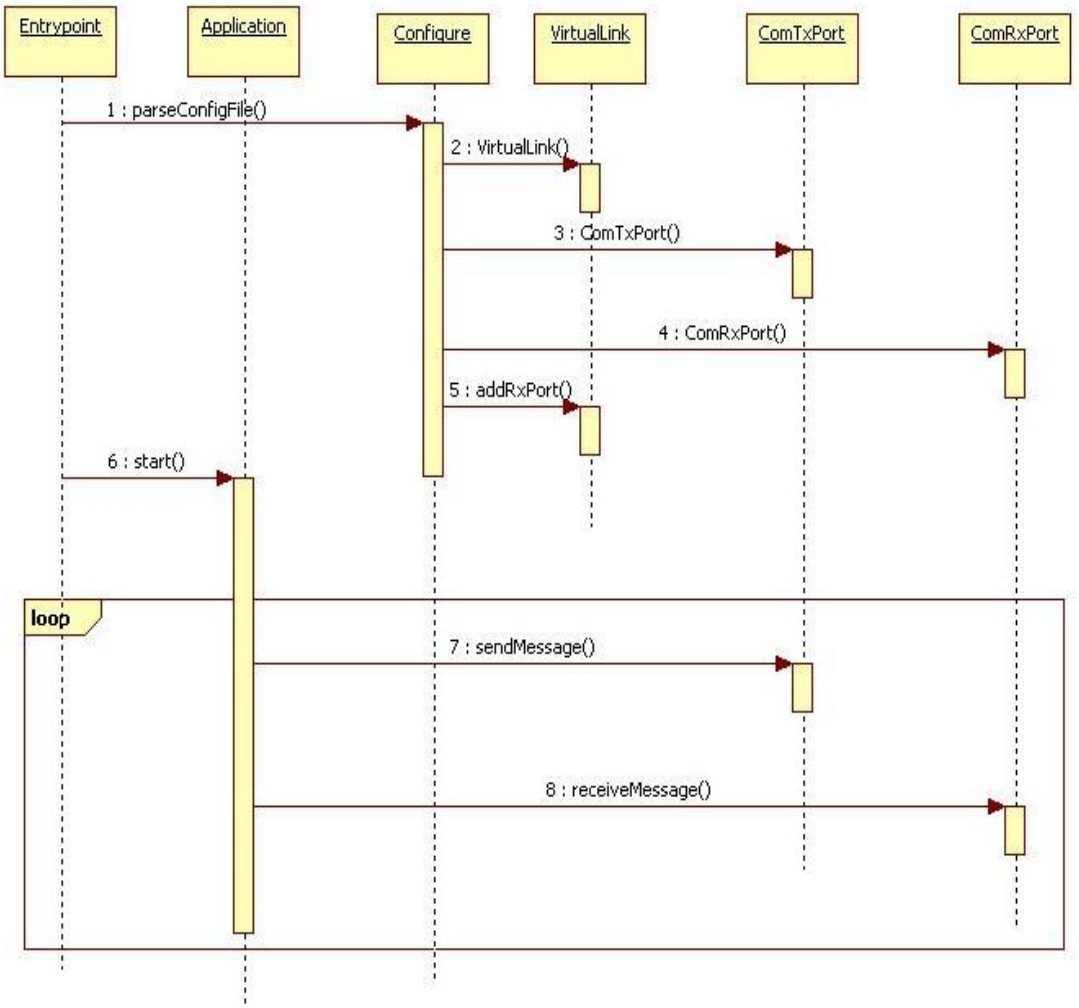
Results from first experiment

Message	Period (ms)	Minimum delay(s)	Maximum delay(s)	Average delay(s)	Packets sent
M1	10	0.000008	0.009865	0.004453	5582
M2	10	0.000000	0.009865	0.004361	5584
M3	10	0.000000	0.009865	0.004485	5587
M4	20	0.000031	0.009850	0.004428	2928
M5	20	0.000015	0.009865	0.004468	2930
M6	20	0.000015	0.009857	0.004459	2932
M7	20	0.000038	0.009857	0.004526	2934
M8	50	0.000969	0.008896	0.004069	1185
M9	50	0.000038	0.009850	0.004684	1186
M10	50	0.000015	0.009827	0.003909	1188
M11	100	0.000053	0.009819	0.004542	600
M12	100	0.000023	0.009811	0.004452	602
M13	100	0.000053	0.009827	0.004509	605
M14	100	0.000046	0.009811	0.004420	607
M15	100	0.000053	0.009834	0.004412	609
M16	100	0.000008	0.009819	0.004416	611
M17	1000	0.000969	0.008766	0.005510	63
M18	1000	0.000977	0.008774	0.005844	66
M19	1000	0.000977	0.008774	0.005572	68
M20	5000	0.002968	0.006927	0.005643	15

Results from second experiment

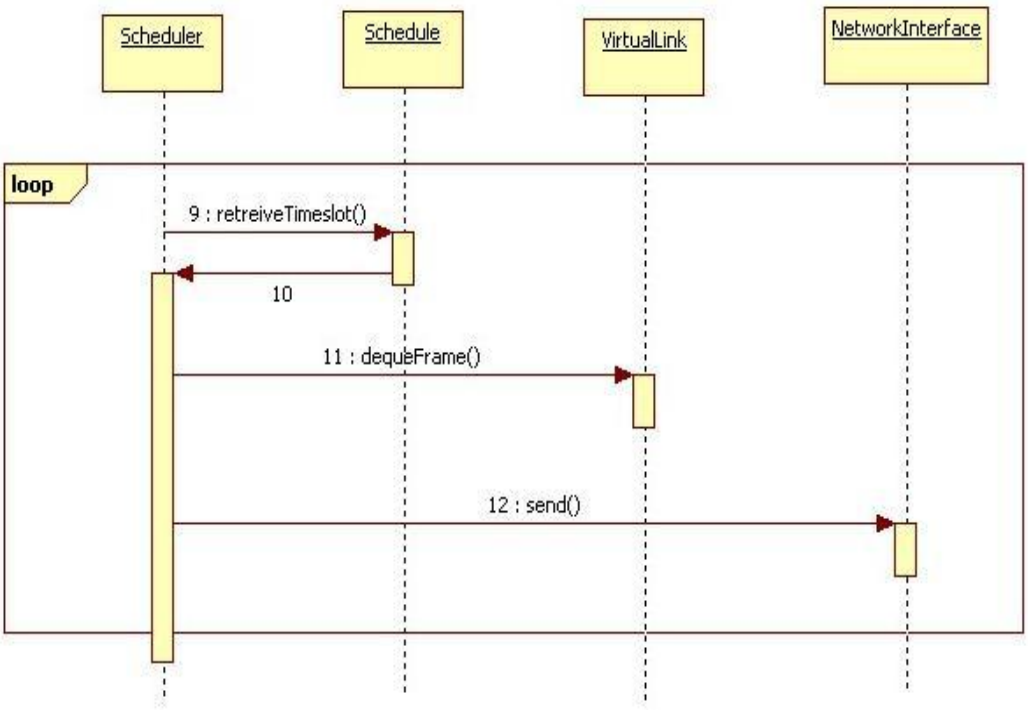
Appendix B Sequence of Execution

On the application side of execution the following occurs. At system startup the configuration file is parsed and the virtual links, transmit and receive ports are created. The configuration file is parsed and contains a list of virtual links with parameters for BAG, Lmax, receive and transmit ports. The software stack starts the traffic scheduler if the system has transmit ports in the parsed configuration file. The software launches all the defined applications for the end system. It is possible for the applications themselves to use the defined transmit and receive ports in asynchronous or blocking mode.



Sequence diagram for the Applications

On the Scheduler side of execution the following occurs. Virtual links are inserted into the schedule based on the BAG value for each link. The scheduler runs in a separate thread and retrieves the current scheduled timeslot. If there are multiple virtual links in the current timeslot they are serialized. It is possible for each virtual link to have multiple transmitting ports. The transmit ports are scheduled in round robin order. The scheduler retrieves the packet and sends it to the network interface.



Sequence diagram for the scheduler

Appendix C List of Abbreviations

802.1Q	Network standard that supports virtual LANs on an Ethernet network. Adds 4 bytes to the Ethernet header.
802.1as	Network standard for timing and synchronization support. Derived from IEEE 1588.
802.1Qat	Network standard for stream reservation.
802.1Qav	Network standard for traffic shaping audio/video streams.
ACK	Acknowledge
AFDX	Avionics Full-Duplex Switched Ethernet
ARINC	Aeronautical Radio, Incorporated. A major provider of transport communication and systems engineering solutions.
ARINC 429	ARINC standard for a 2-wire serial bus with one sender and many listeners.
ARINC 664 Part 7	ARINC standard that describes AFDX.
BAG	Bandwidth Allocation Gap
CAN	Controller Area Network
COO	Coordinator. A gateway node in Scanias in-vehicle CAN network.
CRC	Cyclic Redundancy Check
CSMA/CD	Carrier sense multiple access with collision detection
DARPA	Defense Research Projects Agency
ECU	Electronic Control Unit
EOF	End of Frame
Ethernet AVB	Ethernet Audio Video Bridging
FlexRay	An automotive network communications protocol. Designed to be faster and more reliable than CAN. Supports time triggered communication.

IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
IPG	Inter Packet Gap
LAN	Local Area Network
LMAX	Maximum frame size supported by a virtual link in AFDX
MAC	Media Access Control
MAN	Metropolitan Area Network
PDU	Protocol data unit.
SFD	Start of Frame Delimiter
PGN	Parameter Group Number, A PGN identifies a message's function and associated data in the J1939 standard.
SOF	Start of Frame
PRE	Preamble
TTEthernet	Time Triggered Ethernet
UDP	User Datagram Protocol
VL	Virtual Link in the AFDX protocol. Identifies a unique route from a sender to one or many receivers.
VLAN	Virtual LAN

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