Towards OFDMA-based Ethernet for future in-vehicle communication

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***Abstract*—Autonomous driving and connected car trends have pushed the scalability of the wiring harness in a domain-controller based networks to its limits. A solution is a zonal architecture which organizes the harness and ECU in spacial zones. For the interconnection of the spacial zones a high-performance backbone is mandatory. In this context, the ERIKA project focuses on the development of an OFDMA-based in-vehicle communication backbone. OFDMA, known from wireless (LTE) or powerline communication, provides high performance by multiple simultaneous transmissions over a twisted wire pair using time and frequency multiplexing. In this work, we provide an overview of the project activities and introduce OFDMA-based Ethernet mechanisms for automotive systems. These allow to reduce cabling overhead, handling different traffic classes, support agile software integration, and increase robustness to avoid failures.**

***Index Terms*—automotive Ethernet, OFDMA, OFDMA-based Ethernet, TDMA, FDMA, ERIKA, zonal architecture, backbone bus**

I. Introduction

The complexity of electrical and electronic systems in vehicles has increased steadily in recent decades. In addition, the software components became highly interdependent and interconnected. In the recent years the domain controller-based IVN architecture, shown in Figure 1, were established. Traditionally, more buses have been added to expand the common domains (chassis, powertrain, interior, ADAS) to address growing functionality demands. This has also increased cable harness complexity and made scalability more challenging. However, the current trend of autonomous driving and connected cars have brought this traditional approach to its limits [1], [2].

Data rate and latency requirements are rapidly increasing, driven by sensors and applications for autonomous driving. Standard bus systems such as CAN(-FD), LIN, FlexRay, and MOST are not suitable in terms of data rate, scalability, and flexibility. Switched Ethernet is at the moment state of the art in terms of data volume and speed. Nevertheless, Switched Ethernet is not able to solve the manufacturing problems of the wiring harness.

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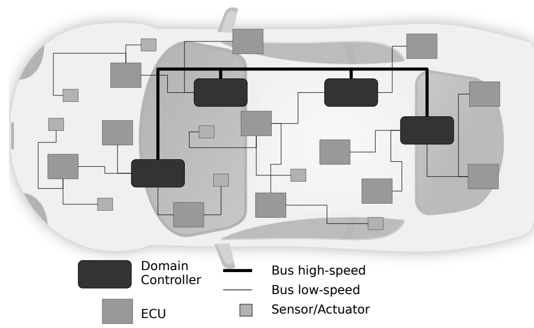

Fig. 1. Domain controller based communication system

These problems motivated the shift to a zonal architecture for the in-vehicle networks (IVN), see Figure 2, to break down the harness into smaller pieces [1], [2], [3]. According to this approach, the in-vehicle network is divided into regions connected by high-speed links – the backbone. In parallel, the links capacity has been also increased e.g. 1 Gbit/s [4] or even 10 Gbit/s and higher transmission speed grades are frequently considered. To achieve these goals, a commonly considered solution for IVNs is Ethernet, extended by the set of extensions for handling timing and latency requirements (Quality of Service) - the Time-Sensitive Networking (TSN) standards [5].

In this context, the project "Elektromobilität mit Redun-

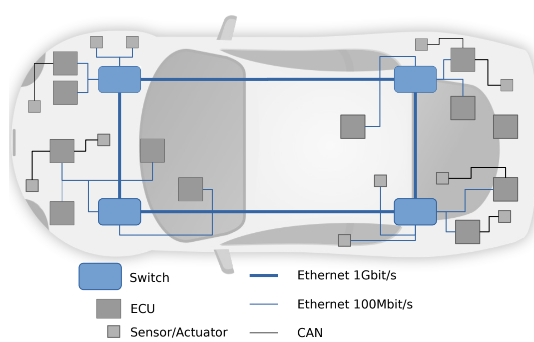

Fig. 2. Zonal backbone communication system

TABLE I
TODAY'S VEHICLE TRAFFIC PROPERTIES AND CLASSIFICATION

Communication Use Case	Data Rate	Frame Length	Latency	Cable Length	Used Standard	Class
SerDes	3-13 Gbit/s	streaming		10 m		A
Ethernet 1000BASE-T1 Ethernet 100BASE-T1	1 Gbit/s 100 Mbit/s	64-1500 Byte	depends on busload and configuration, non deterministic; cameras max 20ms	max 40m	802.1Qav	B
A2B	50 Mbit/s	streaming 32 Channels up and down	<50µs deterministic	15m, max 40m	802.1Qav 802.1AS 802.1Qat 802.1Q VLAN	C
Ethernet with AVB	audio: max 256 channels	streaming up to 256 channels, max frame size 1476 Byte	max 2ms	max 40m	802.1Qav 802.1AS 802.1Qat 802.1Q VLAN	C
Ethernet 10BASE-T1S	10 Mbit/s	64-1500 Byte	dependent on busload and configuration, non deterministic	max 25m	802.1AS	D
FlexRay	10 Mbit/s	0-254 Byte	<10µs deterministic	max 15m	802.1Qbv	E
private CAN/FD	1-2 (8) Mbit/s	11/29 Byte Header 64 Byte Payload	max 100µs	max 20m bei 1MBit/s	802.1Qbv	E
CAN/FD	1-2 (8) Mbit/s	11/29 Byte Header 64 Byte Payload	depends on busload and configuration, non deterministic; as private CAN, P2P deterministic possible	max 20m bei 1MBit/s	802.1Qav or 802.1Qbv	E
CAN	500 kBit/s	11/29 Byte Header 8 Byte Payload	depends on busload and configuration, non deterministic	max 40m	802.1Qav	D
LIN	19.2 Kbit/s	2 Byte Header 8 Byte Payload	depends on configuration of the schedule table		802.1Qav	D
PSI5	125 kBit/s	8/10 Bit Payload	synchron and/or asynchron		802.1Qav	D
discrete extreme	analog signal	analog signal	1-5 ms		802.1Qbv	E
discrete	analog signal	analog signal			802.1Qav	D
802.1Qav = Credit-Based Shaper; 802.1Qbv = Time Aware Shaper; 802.1AS = Time Synchronisation; 802.1Qat = Stream Reservation Protocol;						

danter Intelligenter Kommunikationsarchitektur" (ERIKA) focuses on the introduction of a new high performant backbone bus system offering compatibility to Ethernet. The solution is based on the Orthogonal Frequency Division Multiple Access (OFDMA) technology known from wireless and cable-based communication [6], [7]. Accessing different frequencies with OFDMA enables parallel transmissions on the same cable and, in combination with Time Division Multiplex Access (TDMA), enables a new dimension of flexibility in information distribution. For protocols in the upper layers, the OFDMA-based Ethernet is intended to be transparent to IP communication.

The resulting backbone technology, OFDMA-based Ethernet, enables multiple simultaneous transmissions through time and frequency multiplexing. In such an architecture, current traffic will consume only a fraction of the total frequency bandwidth, leaving room for additional classes of vehicle communication, e.g. sensor data.

In this publication, we summarize the main features of the solution proposed by ERIKA consortium, which include: handling different traffic classes, robustness to permanent failures, reduction of the complexity of the wiring harness, and support agile software development through isolated private resources.

The following structure of the paper is as follows: In section II, we address the requirements for the future IVN. Then, in section III, we briefly describe the operation and main architectural characteristics of the developed OFDMA-based Ethernet backbone. Later, we perform a qualitative evaluation in section IV of this approach by comparing it to a commonly considered automotive Ethernet approach in the context of the requirements from section II. Section V provides the summary of most important findings.

II. REQUIREMENTS TO THE COMMUNICATION IN THE AUTOMOTIVE SYSTEM

To build a backbone communication system for zonal IVN the communication need to be considered more detailed. Table I provides an overview about the different communication use cases in a today's car (see column 1) from the view point of the used bus technology. In a further step this communication use cases are grouped and classified in communication types.

Table I is structured in three ways. **First**: the data rate is decreasing from the top to the bottom. **Second**: there is a distribution in classes highlighted in color or with character A to E in the right column.

- **A** (red): continuous data stream with high bitrate, no frames; hard timing requirements for e.g. stitching of camera pictures.
- **B** (blue): typical Ethernet best effort traffic; no hard timing requirement; Ethernet frames up to 1522 Byte.
- **C** (orange): low latency and stream reservation necessary; e.g. AVB.
- **D** (green): short message frames; no hard timing requirements.
- **E** (yellow): low latency and/or low cycle time; e.g. chassis control or airbag ignition.

Third: the columns "Used Standard" shows a mapping between in Ethernet already available technologies.

Our backbone bus has to fulfill the communication requirements of the classes A to E and some more listed below:

- **Support the development process** due to the possibility of continuous migration in IVN development vs. generation leaps with great breaks.
- **Support software development**
  - Seamless integration in the higher ISO/OSI-layer of Ethernet communication

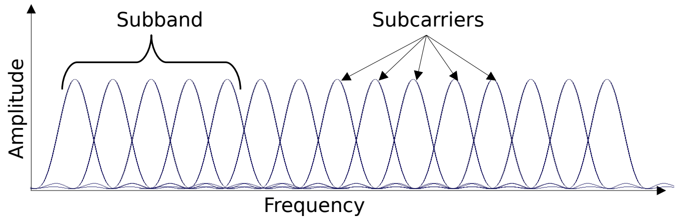

Fig. 3. Correlation between frequency and subcarriers with subbands

- Support of service orientation
- Agile Software development
- **Harness:**
  - Reduce package, weight and number of cables
  - Empower automated manufacturing
- **Flexibility:**
  - Update/extension of HW
  - Intelligent handling of communication technologies (LIN, CAN, FleyRay, ...), e.g. tunnelling
  - Scalability. E.g. over car class, drive technology and ordering options
- **Energy consumption:**
  - Low energy consumption of PHYs
  - Low energy consumption through partial networking
- **Overall reduction of complexity**
- **Cost reductions**
  - Easy integration of components off-the-shelf
- **Security**
  - Use of common standards from Ethernet e.g. MAC-sec
- **Safety**
  - Support of redundancy
  - Self healing and intelligent degradation

III. OFDMA AS POTENTIAL AUTOMOTIVE IN-VEHICLE COMMUNICATION NETWORK

A future in-vehicle communication network has to fullfill the aforementioned requirements. To achieve this a common known technology is used - OFDMA [8]. OFDMA is an extension of Orthogonal Frequency-Division Multiplexing (OFDM) which uses Frequency Division Multiple Access (FDMA). OFDM is widely used in the consumer industry and therefore a well-known technology. It is especially used in mobile communications e.g. WLAN, UMTS, LTE, 5G or in cable-based systems such as DOCSIS or Powerline Communications (PL) [9] (e.g. ITU G.hn [7]). However, the communication channel is highly invariant and suffers possible distortions. To achieve a high performant and robust communication OFDMA uses subcarriers distributed over a frequency range as shown in Figure 3.

A simplified block diagram giving an overview of the OFDMA modulation process is shown in Figure 4. The processing of data starts with the serial to parallel conversion

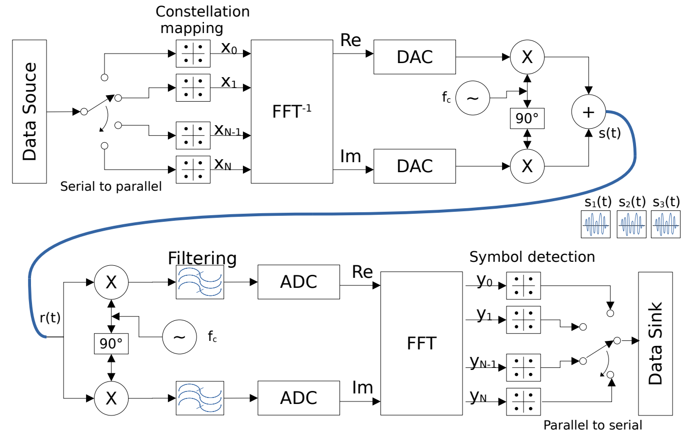

Fig. 4. OFDMA basic function block diagram with IFFT and FFT

to map data to the constellation diagrams. In the next step the Inverse Fast Fourier Function (IFFT) is calculated. Then the digital-to-analog converter (DAC) generates an analog signal. Since, the OFDM Engine is working in time slices, the analog signal is divided and transmitted in so called OFDMA Symbols *s(t)*. For decoding the incoming OFDMA Symbol *r(t)* is filtered and passes the analog-to-digital converter (ADC) and the Fast Fourier Function (FFT) enables the following signal estimation to receive the transported data. OFDMA is capable of fulfilling the desired requirements in terms of data-rate, robustness and adaptability.

This makes it also highly interesting for the use as future in-vehicle communication network. OFDMA supports all types of copper wirings. For a good HF quality of the channel a daisy chain is preferable. In contrast to the common in-vehicle data networks that use a coding scheme to transport the information sequentially. OFDMA allows to modulate information in the frequency domain in parallel on a big number of subcarriers and thereby enabling a new dimension to transport data. The number of subcarriers depends on the quality of the transmission channel, depended of the cable quality, topology and the overall frequency bandwidth.

Furthermore, with the OFDMA based bus the network designer has a greater flexibility to distribute the information

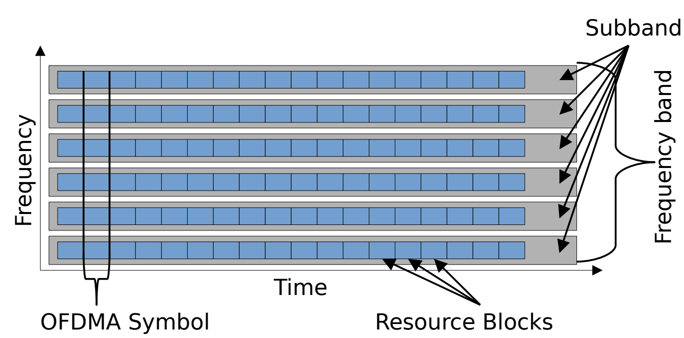

Fig. 5. OFDMA Symbols with frequency and time domain usage with Subbands and Resource Blocks

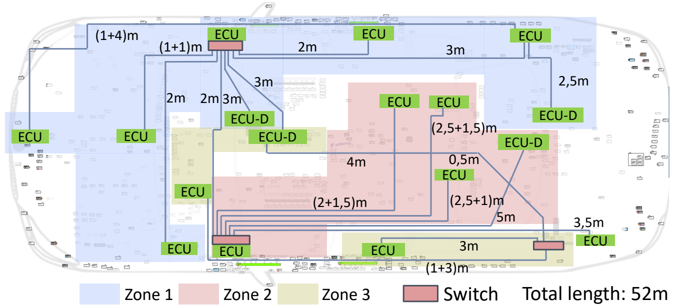

Fig. 6. Ethernet-based backbone with cable length

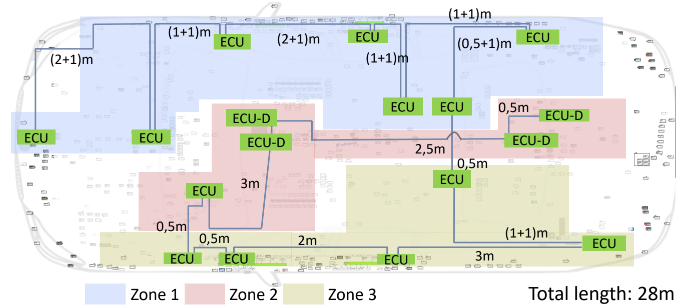

Fig. 7. OFDMA-based Ethernet backbone with cable length

in the time and frequency domain, compared to non OFDMA systems. Data can be transmitted either with a low number or a high number of subcarriers in a subband. First results in a slow transmission second in a fast transmission. In the following, the collection of multiple subcarriers is referred to as a subband.

Figure 5 illustrates the frequency band which is divided into six subbands, each containing several resource blocks. Each resource block is limited in time domain due to OFDMA Symbol length and in frequency domain due to number of subcarriers in a subband. The combination of resource blocks of a time interval is referred as OFDMA Symbol. The distribution of the information into resource blocks that are scrumbled within the time and frequency grid would be a possible application, for example to make sure that external distortions with a small bandwidth or short time interval do not affect the majority of the information. Furthermore the data from lost symbols can be reconstructed by a FEC. Such a distribution of resource blocks is exemplary shown in Figure 8.

IV. Technology comparison

A new zonal IVN backbone must provide flexibility for software integration as well as ensure robustness without increasing the complexity of the harness and violating other requirements discussed in section II. In the following, we describe how OFDMA-based Ethernet addresses these requirements and elaborate which specific features are of interest for backbone deployment. Furthermore, a comparison between OFDMA-based Ethernet features and switched Ethernet solutions is given.

A. Harness

The zonal architecture together with Ethernet or OFDMA-based Ethernet as backbone is a promising solution to reduce harness complexity [1], [2], [3], which is one of the main challenges for future IVNs. Ethernet communication architectures are designed to provide the required bandwidth. Nevertheless, additional features are used to ensure the required limits for transmission latency and deterministic behavior.

In case of switched Ethernet, the network is built with point-to-point connections between switches and end-nodes. With each additional end-node, a port must also be kept available on a switch. This leads to situations where too few or too many ports are available, especially with regard to different configuration variants.

Figure 6 shows a realistic example of an Ethernet-based backbone architecture with the used cable length. It also shows the spatial distribution of the controller along with the zonal allocation. In sum, three switches with three, six and seven Ethernet ports are required to connect each of the 17 control units in the entire vehicle to the backbone. The length of all links is 52 meters.

In contrast to switched Ethernet, a backbone implemented with OFDMA requires only a single cable. Each of the electronic control units (ECU) are connected one after the other to form a daisy chain. Keeping in mind that the data-rate of the backbone should be about one magnitude higher as the links of the switched Ethernet solution. This results in significantly less cabling. Figure 7 shows such a setup with a zonal allocation of 17 ECU connected via an UTP cable. The total length here is 28 m, i.e. 47% less cable compared to the example from Figure 6. Consequently, the advantage of OFDMA-based Ethernet increases as the number of ECUs rises.

B. Advantages of OFDMA

Automotive systems are mixed-critical i.e., they integrate functions which are critical to the passenger safety (thus, carefully designed and tested) with uncritical ones (e.g., multimedia) which behavior are largely unknown. The ISO 26262 standard requires "sufficient independence" supported by Quality-of-Service (QoS) mechanisms ensure that interference between different traffic criticalities is known and bounded.

The IEEE TSN standards for switched Ethernet (considered for automotive applications) provide mechanisms to limit interference and ensure "sufficient independence" between different classes, e.g., prioritization IEEE 802.1Q, traffic shaping IEEE 802.1Qav [10], strict timing separation IEEE 802.1Qbv [11]. All these functions are introduced at layer 2 of the OSI model. This is because in the physical layer all transmissions typically are serialized. Only one packet is transmitted on a connection at any given time (cf. commonly used IEEE 802.3 [12])

In this context, on an OFDMA-based Ethernet link a selected subband is used to transport data over a single wire,

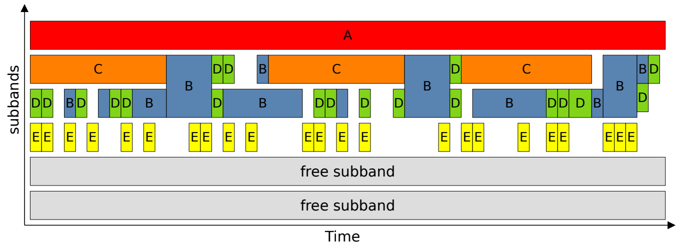

Fig. 8. Frequency assignment to different types of datastreams

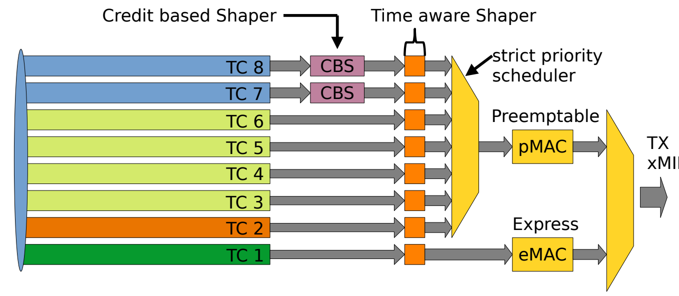

Fig. 9. Egress processing of Ethernet switch port, cf. [13]

cf. overview of the technology in section III. The introduced technology offers an opportunity of parallel transmissions without interference at different frequencies (subbands) using time and frequency multiplexing.

Figure 8 presents an exemplary assignment trace over the time (x-axis) and subbands (y-axis). Data classes from section II are distributed to four subbands and two subbands are reserved. The Figure illustrates a separation between the color highlighted classes where best effort classes (B,C,D) are isolated from time sensitive ones (E). The number of subbands in an OFDMA-based Ethernet depends on the frequency band division cf. III. A trade-off e.g. between number of subbands versus number of subcarriers which build a subband is made by the system designer and the used hardware.

Typical automotive switches support four to eight traffic classes. The TSN arbiter enabling different traffic classes and time-triggered transmission as shown in Figure 9 are designed with layers of shapers. The figure shows eight traffic classes (TC) of which two are shaped with credit-based shaper and together all classes are shaped with time aware shaper and the priority shaper. The complexity arises not only from the implementation of the shapers themselves, e.g., time aware shaper in IEEE 802.1Qbv or credit-based shaper in IEEE 802.1Qav, but also from the queue management mechanisms. Since only one packet can be transmitted at a time, interference causes packets from different traffic classes to accumulate in buffers. In contrast, a simple arbiter in OFDMA-based Ethernet allows the blocked subbands to be bypassed by assigning criticality classes to different subbands. So, for instance, arbitration can be reduced to one level with the same capacity for transporting time-critical data and streaming data, buffer size and queue overhead can be reduced. Moreover, in comparison the number of possible subbands in OFDMA-based Ethernet and therefore the number of supported traffic classes are much higher than possibilities using TSN.

Isolation between traffic classes enables the provision of a private bus for function development teams. A private bus can be realized with one of the free subbands shown in Figure 8. This enables agile software development with an automatic software deployment without running through a complex IVN integration process. State of the art is a complex and time consuming integration process with multiple iterations to eliminate all mostly sporadic failures. Once the development process is complete, the private bus can be integrated into the other subbands so that resources are available for new developments. As a result, OFDMA-based Ethernet facilitates system changes, such as adding data streams to the zonal backbone. It also enables efficient, agile software development for future features without a complex integration process.

C. *Timing aspects with preemption - TDMA*

It is not always possible or required to provide a separate subband for each data class or data stream. This is the reason for transmitting multiple data classes over one subband. Nevertheless, the constraints of the data streams must be adhered in order to meet the time requirements. To achieve this, a common solution is the use of preemption in the shared medium. OFDMA-based Ethernet transmits data symbol by symbol in a TDMA grid. Each symbol is independent from others and consists of several resource blocks, please consider section III for more details.

The following example shows a shared subband access for data stream classes of section II, where a preemption on OFDMA Symbol level have a positive impact.

Considering a subband is working with 256 subcarriers and within each a 512 Quadrature amplitude modulation (QAM) [8] (9 Bit are coded in a QAM 512 cf. constellation mapping 4) the amount of transmitted data for one resource block is

$$256_{subcarriers} * 9_{bit/subcarrier} = 4608\, bit/symbol \qquad (1)$$

So, in consequence an Ethernet frame with 1522 Byte requires three resource blocks to be transmitted. Based on the fact that each resource block is independent, it is possible to preempt the transmitted data class between their individual resource blocks. The scheduler, which arbitrates the medium access

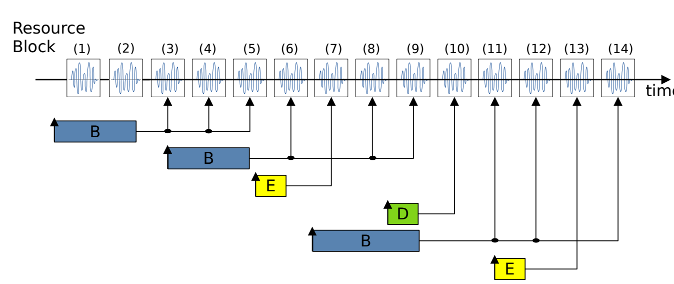

Fig. 10. Assignment of data classes to OFDMA Symbols including preemption for one Subband

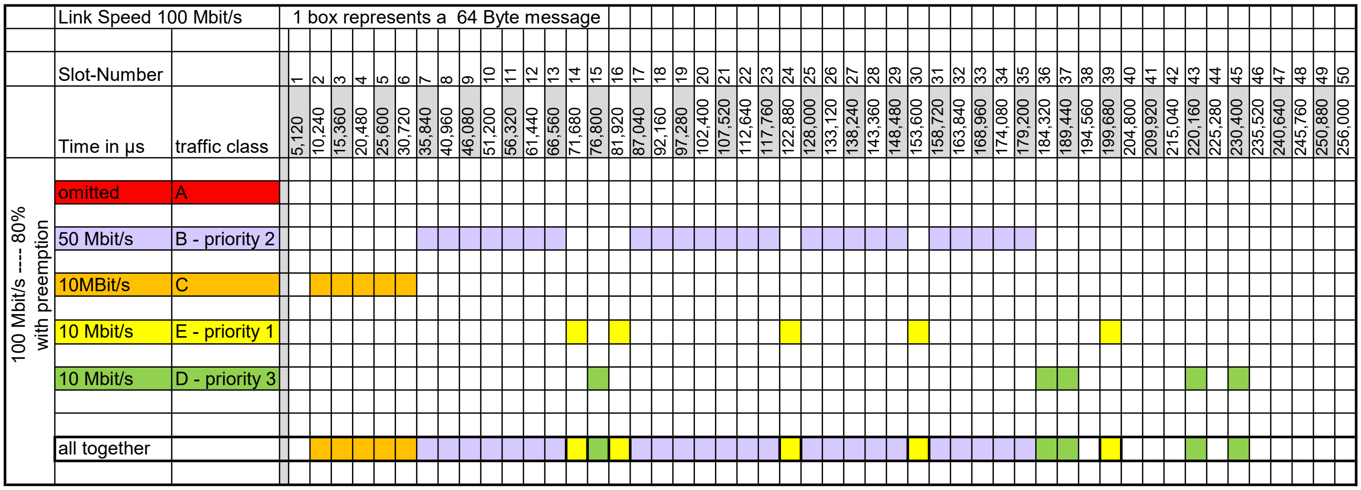

Fig. 11. Example assignment of data classes to Ethernet frames for TSN 100Mbit/s

of OFDMA frequency and time domain, decides for each resource block which data class is allowed to transmit in the current subband. As a result changing the transmitted data class is provided by the scheduler. This leads to a natural preemption mechanism. Figure 10 illustrate the assignment process of incoming data frames of three criticality classes B, D and E to resource blocks. This is indicated by arrows. The numbered rectangles along the x-axis are representing resource blocks. First a frame of class B is allocated to resource block (3), (4) and (5). The second frame of class B is allocated first to resource block (6). Next a frame of class E is ready for transmission and preempt the lower priority frame of class C. Therefore, the next resource block (7) is allocated to class E. After transmission of the resource block class C continues with resource block (8) and (9).

To enable efficient hardware design and data flow, the preparation time t_{pre} of the data frames, the final processing time t_{post} must be similar to the transmission time of the OFDMA Symbol t_{OFDMA}. The preparation time t_{pre} includes scheduling, resource block preparation and encoding. Time t_{post} includes the decoding of received data. In our case each time is equal to $17\mu s$. So, the minimum transport time t_{trans} of a data frame is calculated by the sum of all times:

$$t_{pre} + t_{OFDMA} + t_{post} = t_{trans} = 51\mu s \qquad (2)$$

Therefore, it fits perfect the requirements for a class E communication with a minimum latency of $100\mu s$. Especially because there are no hops in-between on a daisy chain. For the class B data frame, the transport time without preemption is $t_{pre} + 3 * t_{OFDMA} + t_{post} = 85\mu s$ when using a QAM 512 and in case of the preemption $t_{trans} = 102\mu s$. In our example the transport of a critical data frame class E requires $51\mu s$. As a consequence inherent support of resource block preemption leads to short reaction time and reduce latency for critical data classes.

To achieve the same latency with switched Ethernet 100 Mbit/s preemption mechanism is required, since the transmission of one 1522 Byte long Ethernet frame requires $120\mu s$. Figure 11 provide an Ethernet example with 100 Mbit/s link speed. Illustrated is the distribution of data classes and their total amount of bandwidth over the time axis considering the minimum Ethernet frame length of 64 Byte. To achieve the short latency a combination of preemption and guard time intervals are required. The guard time interval guarantees that no frame will start even if it is preemptable, resulting in a delay of the high-priority frames. Slot number 15 in the example represents this case, where a priority 3 frame is sent before priority 2. This priority inversion results of the guard time interval. It prevents priority 2 from being sent, otherwise the timing of the higher priority will be violated. The possible access allocations are further limited by the use of the stream reservation protocol IEEE 802.1Qat for traffic class C.

The same example with 1 Gbit/s Ethernet leads to the result that preemption can be omitted with 1 Gbit/s Ethernet. The transmission time of a 1522 Byte Ethernet frame is about 12 μs and relatively short in comparison with the latencies of the data classes in section II. Guard intervals and time aware shapers remain necessary to achieve timing latency of less than $10\mu s$.

The preemption supported by OFDMA technology provide even for time critical traffic a maximum transmission time without a complex configuration of hardware support.

D. Safety and Redundancy

Functional safety is a predominant requirement for automotive, cf. ISO26262 standard. Therefore, ensuring functional safety is of utmost importance for switched Ethernet as well as for its OFDMA based variant. Furthermore, ISO26262 standard classifies automotive functions into four levels of criticality called Automotive Safety Integrity Level (ASIL) A to ASIL D and unclassified traffic.

On the physical layer, it is therefore necessary to ensure the continuity of transmission even if a component or cable fails to ensure the operation of safety-critical functions e.g. Steer-by-wire or Brake-by-Wire. A redundancy concept is there-

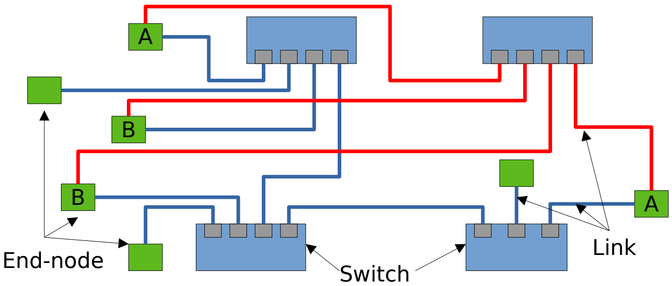

Fig. 12. Redundancy within Ethernet realized with a additional switch and four cables (red)

fore essential. In this section, we compare the two network architectures (switched Ethernet and OFDMA-based variant) in terms of harness complexity for assuring fail-safe vehicle operation.

As discussed in [14] and [15], redundancy protocols can be introduced to enforce the error-free (normal) operation of the network based on switched Ethernet. The straightforward solution of redundancy is duplication. Each packet from safety-critical e.g. (ASIL D) transmissions is send over two fully independent routes from the source to its sink. Such a static resource allocation scheme is proposed by one TSN standard (FRER, IEEE 802.1CB [16]).

Essential for the previously mentioned redundancy mechanism is the duplication of critical components. Figure 12, which is derived from the example of the previous section, shows three switches with connections to the end-nodes on which e.g. a function (A or B) operates. Both of these functions represent safety-critical functions connected by the backbone. Each component (e.g. switches or links) involved in the transport of safety-critical functions must be redundant. In this example at least one additional switch with four links (red links) is added to the network to achieve the required redundancy. Moreover, flexibility during the deployment process is reduced because the ability to move functions from one ECU to another is limited, since not every ECU has a redundant network connection. As a consequence redundancy achieved by duplicating components leads to expensive setups, i.e., a high number of interfaces on each component, complex cabling, less flexibility and higher maintenance.

In the case of the OFDMA-based backbone, redundancy is realized simply by adding a second OFDMA cable, especially since no switches are used. The presence of a second physical layer is required in both technologies. With the possible reduction of the OFDMA backbone cable length by almost 50%, mentioned in the example of the previous section, compared to switched Ethernet. By adding a second cable the redundant OFDMA setup is comparable to the basic Ethernet setup in terms of cable length. Moreover, with the OFDMA-based physical layer, ring topology could be also introduced. The daisy chain is a line topology, both ends of the above mentioned cable can be connected together by a controller that actively forwards messages. Both approaches are presented in Figure 13 which shows end-nodes connected by a OFDMA-

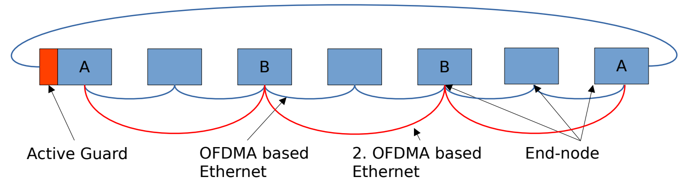

Fig. 13. Redundancy concepts with OFDMA-based Ethernet; either a second cable or a with a active guard

based Ethernet via daisy chain. Also shown is the additional cable (red) to add a redundancy connection for safety-critical functions (A,B). The second approach with the active guard controller and the closed ring topology is shown as well.

The redundancy concepts shown before are focusing either on switched Ethernet or OFDMA-based Ethernet. Both backbone technologies are technologically diverse, so that a combination of both results in a redundant and diverse IVN. For some use cases, it is required to use different technologies to avoid systematic errors. This can be achieved by a combination of switched and OFDMA-based Ethernet.

V. Conclusion

OFDMA-based Ethernet is a promising candidate to be used as a backbone communication system in automotive vehicles. We have shown that OFDMA-based Ethernet is able to handle future challenges e.g. reducing the harness complexity if used as a backbone in a zonal IVN. It also supports compliance with future data transmission requirements, not least because it inherits important TSN properties. For example, the used FDMA provides isolation between traffic classes. In addition, frequency separation enables agile software development which is enabled by isolated private subbands. This allows a complex and time-consuming integration process to bypass. Combined with TDMA, OFDMA-based Ethernet offers great flexibility of controlling data transmissions, e.g. preemption in subbands to achieve timing requirements. The different physical layer compared to Ethernet can provide redundancy for safety-critical systems without increasing IVN complexity too much and adds diversity to the IVN.

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