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Next Generation Wired Intra-Vehicle Networks, A Review

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Abstract— **Automotive electronics is a rapidly expanding area with an increasing number of driver assistance and infotainment devices becoming standard in new vehicles. A review of current networking standards within vehicles reveals a fragmented and proprietary situation with several standards such as MOST, CAN and LVDS dominating, all of which are currently being used by various vehicle manufacturers. Due to the cost of employing a range of networking standards, there is a general desire within the automotive industry to converge on the use of the 802.3 Ethernet for all in-vehicle communication between devices. The introduction of in-vehicle cameras to provide driver assistance applications and the associated high bandwidth requirements of multi camera systems has accelerated the demand for a unifying automotive network architecture. This paper presents an overview of current research present in the literature and identifies trends in the field for the future.**

I. INTRODUCTION

Recent advances in processing power and computer hardware have led to many innovations in the automotive environment. In-vehicle electronic systems are rapidly advancing in complexity and diversity. A multitude of sensors and processors are used in different parts of the vehicle for various functions such as Anti-lock Braking System (ABS) and Electronic Stability Control (ESC), intelligent computer vision safety applications such as lane departure detection and adaptive cruise control, and many others.

The interconnection of sensors and other devices within the vehicle by wireless means, such as RF in the case of Tire Pressure Monitoring Systems (TPMSs) [1] Ultra Wideband [2] or IEEE 802.x based solutions [3], is currently being investigated. While wireless solutions offer advantages over wired systems in that they alleviate cabling requirements, in-vehicle wireless devices still require connection to the electrical power source in the vehicle, negating this advantage. Rouf et al. [4] raise concerns about security in vehicular wireless networks, demonstrating that eavesdropping on a TPMS network and even reverse engineering and injecting false data is possible in a moving vehicle. In-vehicle wired solutions, due to their greater security, bandwidth and reliability in time-sensitive and high bandwidth in-vehicle applications, are expected to be the norm for the foreseeable future.

Historically each new electronic sensor or application would be implemented by adding a new stand-alone Electronic Control Unit (ECU) device and its associated sensors and circuitry, thus organically growing the in-vehicle network as required, often in a heterogeneous fashion. This approach leads to many complex, sandboxed systems in a single vehicle. To overcome this problem, communication links were established between relevant ECUs, allowing ECUs to share data with one another and enabling more advanced functionality. For example, a Transmission Control Unit may provide information to a heads-up display projected on the windscreen [5].

This approach is very inefficient as, with point to point links, the number of connections required increases exponentially with the number of ECUs installed in the vehicle. To overcome this problem, multiple ECUs are connected to one another using bus-based networks such as Controller Area Network (CAN) [6] or FlexRay [7]. Current generation automotive networks are described in more detail in Section II. The use of bus based networks is an improvement on the point to point link system, however it presents its own problems since the number of ECUs connected to a bus increases over time as new subsystems are added to a vehicle, the bandwidth consumed increases significantly. This is generally not an issue for control applications where the required bandwidth is generally low, however the bandwidth issue has been brought into sharp focus by the introduction of infotainment and camera based Advanced Driver Assistance Systems (ADAS) into the vehicle. These applications require significantly more bandwidth than traditional control applications, and as such, the technologies and techniques used on current networks are insufficient for the needs of a next generation in-vehicle network architecture.

It is generally accepted that in order to cope with advancements in technology and the increased role of ADAS systems, the current landscape of a heterogeneous, incremental network based on a variety of networking and software protocols is neither optimal nor desirable. ADAS are continously growing in sophistication, adding features such as lane departure detection [8], driver intent prediction and communication [9]–[11], and real time distance determination systems [12] with many others becoming available. Due to the growing complexity of ADAS, there is a drive within the industry to simplify and standardize approaches towards in-vehicle technology leading to greater reuse and interoperability between OEMs and third party manufacturers.

This paper aims to detail the most recent developments in the field of in-vehicle networking, specifically at the data link layer of the network stack. A number of previous approaches will be examined and the most recent trends and developments discussed.

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TABLE I
CURRENT AUTOMOTIVE PHYSICAL LAYER TECHNOLOGIES

Protocol	Bitrate	Medium	Protocol
LIN	19.2 Kbps	Single Wire	Serial
CAN	1 Mbps	Twisted Pair	CSMA/CR
FlexRay	20 Mbps	Twisted Pair/Optical Fibre	TDMA
MOST	150 Mbps	Optical Fibre	TDMA
LVDS	655 Mbps	Twisted Pair	Serial/Parallel

We aim to identify the key requirements for highly standardized, interoperable next generation automotive networks and outline approaches taken in the literature to achieve this goal.

II. PHYSICAL CONNECTIONS

A. *Current Generation Technologies*

For a number of years, technologies such as CAN, FlexRay, Local Areal Interconnect (LIN) [13], Media Oriented Systems Transport (MOST) [14], Low Voltage Differential Signalling (LVDS) [15] and IEEE 1394 Firewire have been used in vehicles. Each of these communication buses, with the exception of LVDS and Firewire, have been developed specifically for the automotive environment. Table I gives general information on the maximum bandwidth, medium and transmission protocol of each of these technologies.

Navet et al. [16][17] previously carried out two reviews of automotive specific communication protocols. In this section we give a broader introduction than Navet et al. to the most important characteristics of the most common protocols. Nolte et al. [18] gave an overview of many more of the less commonly used protocols. An in-depth exploration of the technical specifics of each of CAN, LIN and FlexRay can also be found in [19].

CAN is an automotive specific bus standard developed by Robert Bosch GmbH released in 1986. It defines layer 1 and layer 2 functionality of the OSI network model. CAN is typically used to transmit control traffic between ECUs within the vehicle. It generally uses a nine pin D-SUB connector and allows for a maximum bus speed of 1 Mbps at lengths of up to 40 metres. Messages are encapsulated in frames with a maximum data field size of 64 bits. It does not use a Time Division Multiplexed Access (TDMA) based MAC layer like the Time Triggered Protocol (TTP) [20] but nonetheless, is currently very popular in the automotive domain as a communication bus for event triggered communication. More deterministic behaviour can be obtained through the use of the Time Triggered CAN (TTCAN) [21] standard at the session layer.

MOST was developed to primarily support networking of multimedia data. The maximum possible bandwidth as defined by the MOST150 standard is 150 Mbps which makes it much more suitable for multimedia data transmission. While the MOST Cooperation published the MOST specification, it lacks specific details relating to the Data Link Layer (OSI Layer 2), making these details available only on a royalty basis.

FlexRay is an automotive networking standard that was developed by the FlexRay consortium which disbanded in 2009. Members of the FlexRay consortium before its dissolution included BMW, Volkswagen, Daimler and General Motors. The main advantages of FlexRay over CAN are its flexibility, higher maximum data rate (10Mbps) and its deterministic, time triggered, TDMA behaviour. However, FlexRay nodes are more expensive than CAN nodes which can be unappealing for high volume manufacture. It provides constant latency and jitter through clock synchronisation. Its tight latency and time characteristics mean that is is often used as part of 'drive-by-wire' applications where deterministic performance is critical. A similar standard is TTP [22].

LIN [23] is an inexpensive, broadcast, master-slave, serial communication bus developed in the late 1990s by the LIN Consortium consisting of a number of automotive manufacturers. It arose from a desire for a cheaper alternative to CAN for less important elements of the in-vehicle network.

Low Voltage Differential Signalling [15] (LVDS) is a high speed signalling standard that uses twisted pair copper cables. While not explicitly developed for automotive applications, the high bandwidth made possible by LVDS (up to 655 Mbps) has made LVDS an attractive option for automotive camera manufacturers.

IEEE 1394 [24], more commonly known as Firewire, is a general computer communication bus standard often used in consumer video cameras, which has been proposed as a candidate backbone network for automotive infotainment traffic [25]. It can often be found in automotive grade cameras from various manufacturers, however it has been superseded by Ethernet based devices in recent years.

B. *Ethernet*

Ethernet [26] is a very common communication bus, it is the communication technology of choice for much of the Internet and is low cost, fast and flexible.

The primary driver of Ethernet in vehicles is the increased bandwidth that it offers. Legacy technologies such as CAN and MOST were developed specifically for automotive applications, and as such offer the advantage that they are tailored with in-vehicle communication in mind. Upon their inception, the bandwidth levels provided were sufficient for the applications that they carried out but this is no longer the case. To solve this problem, automotive manufacturers are seeking to migrate automotive communications to an Ethernet based solution.

III. LINK LAYER PROTOCOLS

As has been discussed in Section II, the bandwidth capabilities, cost and flexibility of 802.3 Ethernet make it a very attractive option for the interconnection of automotive devices. As such, there are a number of publications in the literature which discuss the use of 802.3 Ethernet in automotive scenarios, often including the use of 802.1Q priority tagging and traffic shaping to improve performance [27]–[30]. While the conclusions drawn from these papers are universally positive towards the use of Ethernet in the automotive domain, automotive specific technologies such as FlexRay still provide a major advantage which is not present in 802.3 Ethernet, namely deterministic TDMA behaviour.

Network communication can very generally be split into two types, event-triggered and time-triggered. Latencies of traffic within an event triggered network can be probabilistically modelled based on network parameters, while those in a time triggered systems are fixed. Ethernet and CAN are event triggered network protocols while FlexRay is time triggered. This means that without modification, for certain safety critical applications such as 'drive-by-wire', Ethernet cannot be used as it cannot guarantee deterministic behaviour.

There are a number of proposed approaches to overcome this problem in the automotive domain, though two of these are most common in the literature, namely Audio Video Bridging Ethernet (AVB), and Time Triggered Ethernet.

A. Audio Video Bridging

AVB consists of a set of four IEEE standards designed to provide time synchronized streaming of audio and video sources using 802.3 Ethernet.

The standards that together comprise AVB are as follows :

- IEEE 802.1AS: Timing and Synchronization for Time-Sensitive Applications (gPTP),
- IEEE 802.1Qat: Stream Reservation Protocol (SRP),
- IEEE 802.1Qav: Forwarding and Queuing for Time-Sensitive Streams (FQTSS), and
- IEEE 802.1BA: Audio Video Bridging Systems

Each of these standards plays a role in the provision of time synchronized performance on an Ethernet network. 802.1AS utilises the IEEE 1588 Precision Time Protocol standard to allow for precise time synchronisation between nodes. This involves the use of a grandmaster node which communicates timing information to all other nodes on the network.

802.1Qav handles priority allocation of streams by adding data to the Ethernet header in a very similar way to the 802.1Q standard commonly utilised in VLANs.

Streams within an Ethernet AVB capable network can reserve bandwidth using the 802.1Qat standard, by issuing a Stream Reservation Protocol (SRP) message. Resources are then allocated in both end nodes and each of the transmit nodes along the path at the Link Layer (or Level 2) of the OSI model.

Finally 802.1BA provides functionality to identify AVB profiles and nodes within a network.

AVB supports two traffic classes, with different latency guarantees. *Class A* traffic maps to 802.1Q priority level 3, and offers a delay guarantee of 2ms. *Class B* provides delay guarantees of 50ms and is mapped to 802.1Q priority level 2 [31].

Although the initial scope of the AVB standard was for the time synchronized delivery of audio and video content for stage and live environments, its potential for use in other scenarios that require time sensitive delivery of traffic was quickly realised. The interest in its use in these domains has led the IEEE group in charge of the AVB standard to begin work on a second revision set to include several improvements to facilitate automotive, industrial and consumer requirements. The AVnu Alliance [32] supports these operations and the development of associated IEEE standards. Its members include a number of first tier automotive manufacturers and component manufacturers. These proposed improvements include pre-emption, which would mitigate the problem of Head of Line Blocking (HoLB), a topic explored in more detail in Section III-A.1 below.

1) Aeronautical and Industrial Applications: Imtiaz et al. [33] carried out a performance study of the suitability of AVB technology for industrial applications, comparing AVB with 802.3 Ethernet and also AVB using a credit based traffic shaper. The authors noted that the transmission of a large best-effort traffic frame (HoLB) can interfere with the operation of normal AVB transmission. They conclude that, for the particular simulation scenario tested, AVB does not offer advantages over 802.3 Ethernet.

In [34], the same authors propose a method to overcome the effects of head of line blocking in Ethernet AVB networks. In order to ensure that a real time priority packet is not blocked on the network by a large, non real time packet, the authors propose stopping transmission of the non real time packet and fragmenting it, transmitting the real time packet and finally, resuming transmission of the non real time packet again. Simulated results from this work showed promise that the use of this strategy would mitigate the effects of HoLB on AVB networks and as such should be considered for the second generation of the AVB standard.

Heidinger et al. [35] created a prototype AVB capable network for an aeronautical audio based network. The authors concluded that the network was a viable replacement for legacy networks, and provided satisfactory delay values, but raised concerns about certification of AVB capable hardware.

2) Automotive Research: Lim et al. have carried out a number of analyses of Ethernet AVB specifically with regards to its use in the automotive domain [36]–[38]. In [37] the authors provide a comparison of the performance of 802.1Q priority scheduling and the more advanced AVB in a simulation environment using the OMNeT++ network simulator.

The end-to-end delay results of this comparison show 802.1Q prioritisation outperforming AVB for the transmission of control data within the vehicle, when that control data is assigned the highest 802.1Q priority value and is assigned a best-effort priority value within the AVB network.

However, when extra load is introduced to the network, AVB *Class A* or *Class B* video traffic does outperform the same traffic in the 802.1Q network. The authors conclude that more work is required in the area to ensure that within an AVB network, control traffic manages to satisfy its real time requirements.

Work to ensure the suitability of AVB in a harsh automotive environment has been carried out by Kern et al. [39]. The authors perform tests on a simple prototype network to ensure that AVB capable devices perform as expected under varying temperature conditions. The authors conclude that temperatures between -10°C and +70°C do not cause problems for AVB capable consumer devices. This is an important result for the use of AVB within vehicles.

In [31], Zinner et al. address the issue of integrating legacy automotive networks with Ethernet AVB networks, specifically MOST and FlexRay networks. This is a pertinent problem as it is unlikely in the near term that all devices in the vehicle will be immediately replaced with Ethernet capable replacements. Instead the change is likely to be gradual and evolutionary rather than revolutionary. Because of this, Ethernet will likely have to coexist with some legacy networks for a period of time.

Specifically, in [31] the authors propose a system to translate the QoS guarantees provided by MOST and FlexRay to an AVB network, while crucially also maintaining synchronisation between clocks across the bridged networks. This work however relies on simulation and somewhat ideal networks and more work is required to validate its feasibility in a real network with multiple FlexRay ECU devices and clusters.

3) Mathematical Analysis: Much of the work cited above involves the use of simulation or prototype networks to test the performance and characteristics of AVB networks. However also important are more formal mathematical explorations of the technology. Work of this nature can also be found in the literature.

Diemer et al. [40] provide a mathematical worst case timing analysis of the AVB standard for an industrial application, resulting in a formula for the worst case end-to-end latency value in an AVB network, as a function of switch transfer time, packet blocking by other packets and traffic shaping delay.

In [41], Queck provides an analysis of the AVB standard through the lens of network calculus [42]. In this work, the authors provide a formal derivation of the worst case end-to-end delay values under the assumptions of the Network Calculus framework and apply these to a case study consisting of a double star automotive network with 3 traffic classes. The authors conclude that, under the assumptions made in deriving the presented worst case analysis, that AVB, and specifically 802.1Qav as a queuing paradigm, meet the timing requirements of automotive traffic.

B. TTEthernet

TTEthernet or Time Triggered Ethernet [43], first presented by Kopetz et al. [44][45][46], is another Ethernet based candidate for real time communication in automotive or industrial networks. It is designed to allow for the coexistence of time triggered real time, synchronized communication with lower priority event triggered messages over Ethernet. This is implemented by applying a Time Division Multiplexing scheme with a time granularity of 60μs, on top of existing 802.3 Ethernet.

TABLE II
AUTOMOTIVE NETWORK TRAFFIC TIMING REQUIREMENTS

Traffic Class	Max End-to-End Delay	Service Rate
Control Data	2.5ms [52]	10 - 100ms
Safety Data (Video)	45ms [27]	0.05 - 1ms
Infotainment Data	150ms [53]	~1ms

TTEthernet supports three different traffic types, Time Triggered (TT), Rate Constrained (RC) and Best Effort (BE). TT traffic takes priority over all other types, while RC traffic is guaranteed to be supplied with a predetermined bandwidth level. BE traffic follows standard Ethernet procedures.

One of the main stated advantages of TTEthernet is that TTEthernet switches allow for preemption, that is, lower priority messages are interrupted and stored in the switch buffer to allow TT messages to take priority. This eliminates the problem of HoLB mentioned in Section III-A.1 and is one of the features currently being investigated for inclusion in the second revision of the Ethernet AVB standards.

TTEthernet is standardized in SAE AS6802 [47] by the Society of Automotive Engineers and developed by TTTech. Similar to Ethernet AVB, in order to use the system, switches within the network must implement the TTEthernet standard.

Steinbach et al. [48] compared the suitability of TTEthernet with FlexRay using calculations on typical scenarios for both standards. Jitter and latency were found to be comparable between both technologies and taking into account the much higher bandwidth available in TTEthernet, it was found to be a viable replacement for FlexRay networks for time triggered communication in vehicles.

Simulation based results, also from Steinbach et al. [49] validate closely the mathematically demonstrated results from [48].

In [50], Bartols, Steinbach et al. analysed the performance of TTEthernet using commercially available hardware, a basic network topology and TTTech developed TTEthernet protocol stack. The results of this hardware testing showed latency values when using a TTEthernet switch were much more stable than those obtained when using a normal Ethernet solution.

Muller et al. [51] demonstrated an ARM based SoC implementation of TTEthernet specifically for automotive applications.

The papers explored above only seek to give an overview of research found in the literature as it relates TTEthernet to automotive applications. TTEthernet is also being investigated in a number of other domains where real-time communication is required.

IV. CONCLUSIONS

It is clear from the literature and the significant industry interest through groups such as AVnu and OPENSIG that Ethernet represents the most likely and promising candidate for the standardization of next generation automotive networks. The benefits of a wide scale adoption of Ethernet are wide ranging and include bandwidth improvements, cost savings and improved implementation flexibility. Since Ethernet is a widely used and recognised IEEE standard, the automotive industry will benefit from its continued evolution and improvement.

However, as discussed in this paper, there are challenges to using Ethernet in the automotive environment. The most important of these is carrying time sensitive control traffic throughout the vehicle. For this reason, it becomes necessary to employ additional queueing, timing and scheduling techniques on top of 802.3 Ethernet. Previous work in this endeavour as discussed at the beginning of Section III involved the use of 802.1Q priority tagging as well as traffic shaping algorithms to provide low average delay values across an Ethernet network to meet automotive requirements as set out in Table II.

More recently, much work has been carried out on more complex solutions such as Audio Video Bridging and TTEthernet. Both approaches show promising results in the provision of real time performance for time sensitive traffic across automotive Ethernet networks. However, the volume of work in the literature, and the membership of several tier 1 automotive manufacturers in the AVnu alliance point to AVB as being the most likely candidate to succeed. A competitive simulation based analysis of AVB and TTEthernet carried out by Steinbach et al. [54] shows that both technologies provide comparable results in the delivery of time sensitive automotive traffic. Though AVB has been shown to be affected more than TTEthernet by cross traffic on the network, it offers advantages through the reliable streaming of multimedia data.

Each technology has relative strengths and weaknesses in an automotive environment, however we propose that both the IEEE standardization and wide membership of the AVnu working group, point towards Ethernet AVB becoming the dominant technology in the automotive domain. Ultimately the adoption of either of these strategies will depend on the availability of cost effective components and devices that implement the standards, and it appears that in the future, this will favour AVB.

It is likely that the shift towards fully Ethernet based automotive networks will be evolutionary and not revolutionary. It is not currently not feasible to replace all current in-vehicle devices with Ethernet enabled replacements. Therefore it is likely that Ethernet will function as a high speed backbone network at first, coexisting with legacy technologies until such time as it becomes cost effective to migrate to a full, end-to-end Ethernet solution.

This paper presents evidence that as in-vehicle technology becomes more and more complex, there is a drive to standardize approaches across the board, allowing manufacturers to focus on innovating on exciting applications instead of underlying architectures. This provides a good framework for the future expansion and improvement of in-vehicle systems, leading ultimately to greater driver comfort and most importantly, safety.

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