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Intra-Vehicle Networks: A Review

Shane Tuohy, Martin Glavin, *Member, IEEE*, Ciarán Hughes, Edward Jones, *Member, IEEE*, Mohan Trivedi, *Fellow, IEEE*, and Liam Kilmartin, *Member, IEEE*

***Abstract*—Automotive electronics is a rapidly expanding area with an increasing number of safety, driver assistance, and infotainment devices becoming standard in new vehicles. Current vehicles generally employ a number of different networking protocols to integrate these systems into the vehicle. The introduction of large numbers of sensors to provide driver assistance applications and the associated high-bandwidth requirements of these sensors have accelerated the demand for faster and more flexible network communication technologies within the vehicle. This paper presents a comprehensive overview of current research on advanced intra-vehicle networks and identifies outstanding research questions for the future.**

***Index Terms*—Audio video bridging (AVB), automotive Ethernet, controller area network (CAN), driver assist, in-vehicle networking, low-voltage differential signaling (LVDS), media oriented systems transport (MOST), time-triggered Ethernet (TTEthernet), 802.3.**

I. Introduction

RECENT advances in computer hardware and processing power 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. Antilock braking system (ABS) and electronic stability control are examples of systems that monitor a vehicles' internal performance and dynamics; whereas camera, radar, and ultrasonics sensors are being used to sense the environment around the vehicle and provide drivers with more information about their surroundings.

The wireless interconnection of sensors and other devices within the vehicle, such as radio frequency in the case of tire pressure monitoring systems (TPMSs) [1], ultrawideband [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, which mitigates this advantage. Rouf *et al.* [4] raised concerns about security in wireless networks, demonstrating that eavesdropping on a TPMS network, and even reverse engineering and injecting false data, is possible in a moving vehicle. Due to the absolute need for reliability and security in safety-critical systems, wired solutions are expected to dominate for the foreseeable future.

Historically, each new electronic sensor or application in a vehicle has been implemented by adding a new stand-alone electronic control unit (ECU) device and subsystem. This has led to in-vehicle networks growing in both size and complexity in an organic fashion. This often leads to many complex sandboxed heterogeneous systems in a single vehicle. This is undesirable as there can be a number of different network protocols in use, which inhibits communication between systems. It also increases cost to the manufacturer in terms of hardware costs, development costs, and support costs.

To overcome these problems, communication links were established between relevant ECUs, allowing ECUs to share data with one another and enabling more advanced functionality. For example, the ABS subsystem may communicate with a seat belt pretensioning system to activate it in the event of a collision. This approach is very inefficient as, with point-to-point links, the number of connections required exponentially increases 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) [5] or FlexRay [6]. Current generation automotive network technologies such as these 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, as the number of ECUs connected to a bus increases over time, the bandwidth consumed significantly increases. The question of bandwidth does not generally manifest as a significant issue in control applications within the vehicle due to the limited bandwidth requirements of the sensors involved. However, the bandwidth issue has been brought into sharp focus through the introduction of infotainment and camera-based Advanced Driver Assistance Systems (ADAS). These applications significantly require 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.

Recently, there has been a general desire within the automotive industry to streamline the development of these systems through standardization of technologies between manufacturers, leading to greater reuse and interoperability between original equipment manufacturers and manufacturers. Most major automotive companies are members of one or more special interest groups and bodies centered around this goal. These bodies include the One Pair EtherNet Special Interest Group (OPENSIG) [7], the AVnu alliance [8], and the Japanese Automotive Software Platform and Architecture (JasPar) group [9].

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S. Tuohy, M. Glavin, E. Jones, and L. Kilmartin are with the College of Engineering and Informatics and the Connaught Automotive Research Group, National University of Ireland, Galway, Ireland (e-mail: shane.tuohy@nuigalway.ie).

C. Hughes is with Valeo Vision Systems, Galway, Ireland.

M. Trivedi is with the Laboratory for Intelligent and Safe Automobiles, University of California, San Diego, La Jolla, CA 92093 USA.

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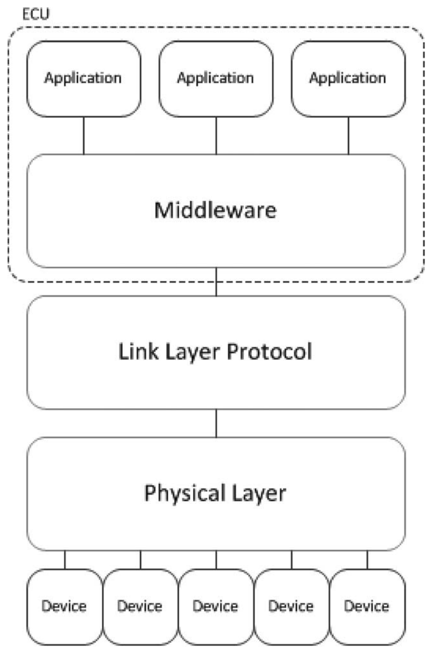

Fig. 1. Layered view of an automotive communication network.

This paper aims to comprehensively describe the most recent developments in the field of in-vehicle networking at all levels of the network stack, from the underlying physical layer connection and the data link layer to the operating systems on which next-generation ADAS will run. Each level of the automotive software stack illustrated in Fig. 1 will be explored, and the most recent trends and developments will be discussed.

This paper is a revised, much expanded, and up-to-date expansion of the review published in [10]. This work includes a more in-depth exploration of physical layer technologies for next-generation Ethernet networks, as well as of important middleware technologies in use in the automotive industry. We also provide high-level discussion on the overall future direction of each of the explored areas based on trends identified from published research in this area. We aim to identify the key requirements for a highly standardized interoperable next-generation automotive network and outline approaches taken in the literature to achieve this goal. Section II explores the characteristics of the most popular physical layer technologies in use in automotive networks. Section III details the types of traffic found on an automotive network and their broad classification types. Section IV explores the role of Ethernet in the next-generation of automotive networks, whereas Section V discusses link layer technologies such as audio video bridging (AVB), time-triggered Ethernet (TTEthernet), and others. Section VII discusses the use of a common middleware operating system technology for automotive applications across manufacturers. Finally, Sections VIII and IX contain discussions on the future directions of research in this area and our conclusions, respectively.

II. Physical Layer Technologies

A. Automotive-specific Technologies

For a number of years, technologies such as CAN [5], FlexRay [6], local interconnect network (LIN) [11], media oriented systems transport (MOST) [12], low-voltage differential signaling (LVDS) [13], and IEEE 1394 Firewire [14] have been used in vehicles. Each of these communication buses, with the exception of LVDS and Firewire, have been specifically developed for the automotive environment. Table I provides general information on the maximum bit rate, medium, and transmission protocol of each of these technologies.

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

Navet *et al.* [15]–[17] previously carried out reviews of automotive-specific communication protocols. These papers are excellent sources for technical information on automotive communication technologies, which is outside the scope of this paper. Here, we broaden the discussion 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 CAN, LIN, and FlexRay can be also found in [19]. Finally, Karagiannis *et al.* [20] and Gerla and Kleinrock[21] provided excellent and comprehensive overviews of the general area of vehicular networking, focused mostly on intervehicle networking and vehicular ad hoc networking.

CAN is an automotive-specific bus standard developed by Robert Bosch GmbH, which was released in 1986 [5]. It defines layer-1 and layer-2 functionality of the Open Systems Interconnection (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 Mb/s at lengths of up to 40 m. 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 media access control layer such as the time-triggered protocol (TTP) [22] but, nonetheless, is currently very popular in the automotive domain as a communication bus for event-triggered communication. More deterministic behavior can be obtained through the use of the time-triggered CAN [23] 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 Mb/s, which makes it much more suitable than CAN for multimedia data transmission. While the MOST Cooperation published the MOST specification [12], 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 (GM). The main advantages of FlexRay over CAN are its flexibility, higher maximum data rate (10 Mb/s), and its

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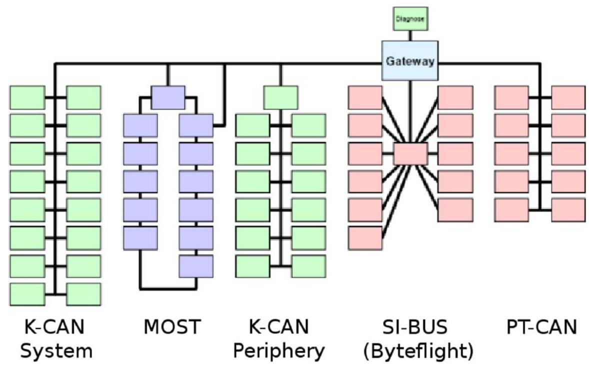

Fig. 2. BMW 7 series architecture [27].

deterministic time-triggered TDMA behavior. 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 synchronization; these characteristics mean that it is often used as part of "drive-by-wire" applications, where deterministic performance is critical. The TTP is a similar standard and was compared with Flexray by Kopetz *et al.* in [24].

LIN [25] 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.

B. Non-automotive-specific Standards

LVDS [13] is a high-speed signaling standard that uses twisted pair copper cables. While not explicitly developed for automotive applications, the high bandwidth made possible by LVDS (up to 655 Mb/s) has made LVDS an attractive option for automotive camera manufacturers.

IEEE 1394 [14], which is 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 [26]. It is often supported by automotive-grade cameras from various manufacturers; however, it has been superseded by Ethernet-based devices in recent years.

III. Automotive Network Traffic

As detailed in Section I, in the past, new electronic subsystems and applications have been added to existing automotive systems through the addition of a new ECU and associated communication infrastructure. This has resulted in extraordinarily complex in-vehicle networks, sometimes containing in excess of 100 separate ECUs, as illustrated in Fig. 2, which shows a part of the architecture of a BMW 7 series network from circa 2006 [27].

The types of devices commonly found in modern automotive networks are varied and have different communication requirements. To simplify their classification, they are generally separated into a number of discrete categories [28], which are detailed below.

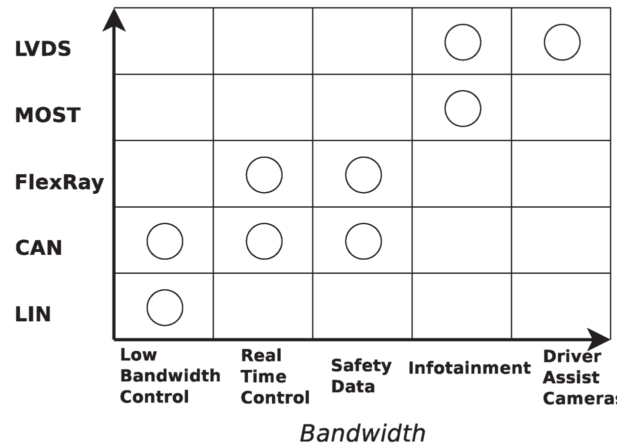

Fig. 3. Mapping of traffic types to network technologies.

A. Control Data

1) Low-bandwidth Control Applications: These are control subsystems within a vehicle that require low bandwidth, with low quality-of-service (QoS) demands. These include systems that control aspects of the vehicle that are not safety critical, for example, comfort subsystems such as electronically controlled seats and mirrors.

2) Real-time Control Applications: These are systems within a vehicle that have relatively low bandwidth requirements but high/real-time QoS requirements, e.g., suspension and braking systems, ABS, traction control, and others. Generally, in modern vehicles, these systems utilize a CAN bus network, which provides low bandwidth but high reliability.

B. Safety Data

Increasingly modern vehicles come equipped with a number of built-in driver assist safety systems. These can include adaptive cruise control using LIDAR or RADAR sensors, parking sensors, and nighttime pedestrian detection using infrared sensors.

C. Infotainment Data

Infotainment traffic encompasses all network traffic related to entertainment and driver information systems within a vehicle. This includes Global Positioning System systems, display-only camera feeds, audio and visual entertainment, and miscellaneous other network traffic (e.g., a 3G/UMTS/4G Internet connection).

D. Driver Assistance Cameras

Driver assistance cameras are increasingly common in vehicles. They require high bandwidth and, depending on the application, high QoS. These can include passive systems such as reversing cameras for display to the driver or active systems such as lane departure detection using front and rear optical cameras [29].

An illustration of the mapping of these types of traffic to the network technologies described in Section II is shown in Fig. 3.

IV. Ethernet

Ethernet [30] is a commonly utilized communication bus, which is the communication technology of choice for much of the Internet due to its cost, speed, and flexibility.

A motivating force for Ethernet for use in vehicles is the increased bandwidth that it offers. Legacy technologies such as CAN and MOST were specifically developed for automotive applications and, as such, offer an advantage in that they are tailored with in-vehicle communication in mind. At the time of their inception, the bandwidth levels provided were sufficient for the applications that they supported, i.e., by modern standards, low-bandwidth control applications, but this is no longer the case.

Ethernet has already superseded CAN bus connections for interfacing with diagnostic equipment due to its increased bandwidth. In [31], the authors gave an the example of the time taken to flash the firmware of a vehicle. Using a CAN-based network, this process takes 10 h when flashing an 81-MB firmware update. Using an Ethernet network and a much larger 1-GB update, this procedure takes 20 min.

Driver assistance applications are a rapidly expanding area of research. The placement of a variety of sensors around and throughout a vehicle allows for the development of new and exciting safety features such as collision avoidance, lane departure detection, traffic sign classification, blind spot detection, driver intent detection [32], pedestrian detection, automatic cruise control, and many others. These sensors are being used to communicate information to the driver in useful and innovative ways [33].

These applications take advantage of high-bandwidth sensors around the vehicle, such as 24-GHz short-range or 77-GHz long-range RADAR sensors [34], ultrasonics, infrared cameras [35], and RGB optical video cameras [36].

In (1), we estimate the raw bandwidth requirements of a single 1280×960 pixel resolution camera stream at 30 frames/s, with a depth of 8 bits per pixel for each of the red, green, and blue color channels. This calculation assumes the transmission of uncompressed video, which is not uncommon among currently commercially available Ethernet camera modules. The transmission of uncompressed video is far beyond the capabilities of current generation technologies but could be supported using gigabit Ethernet. Thus

$$\begin{aligned} \text{Bandwidth} &= (\text{Height})(\text{Width})(\text{FPS})(\text{Bits Per Pixel}) \\ &= (1280)\ (960)\ (30)\ (24) \\ &= 884.74\ \text{Mbps}. \end{aligned} \tag{1}$$

A. Unshielded Twisted Pair Ethernet

Many of the advantages of Ethernet (not directly related to the higher bandwidth that it provides) are due to the proposed use of unshielded twisted single-pair (UTP) cabling. The OPENSIG describes itself as a group aiming to "address industry requirements for improving in-vehicle safety, comfort, and infotainment, while significantly reducing network complexity and cabling costs" [7]. It promotes the use of UTP cabling by automotive manufacturers and counts among its members BMW, Daimler, Nissan, and Renault.

Cabling in an automotive environment is a complex problem. Much of the physical space within a vehicle is taken up by the passenger cabin, and cables cannot be routed through this area. UTP Ethernet consists of a single twisted copper wire pair, making it small, flexible, lightweight, and cheap to manufacture. It allows manufacturers to make space and weight savings in the routing of cable harnesses while also improving available bandwidth.

The use of UTP cabling allows the Ethernet to fulfill important automotive specific requirements such as electromagnetic compatibility (EMC) requirements. BMW testing [37] has shown that 100-Mb/s full-duplex UTP cabling meets automotive EMC requirements. Moreover, Hank *et al.* [38] have explored in detail a commercially available automotive-targeted 100-Mb/s product, from network equipment vendor Broadcom.

However, 100-Mb/s Ethernet is only capable of carrying compressed video streams, as illustrated by (1). The IEEE Reduced Twisted Pair Gigabit Ethernet (RTPGE) Study Group [39] was founded in November 2012 specifically to standardize modifications of the IEEE 802.3 standard to allow for the use of 1-Gb/s Ethernet on fewer than three pairs of twisted copper cable. This is required as the current 802.3 standard does not support 1-Gb/s operation on fewer than four twisted pairs. The aims of the group specifically mention the use of Ethernet as a communication network in vehicles as a primary driver behind the development of these new additions to the 802.3 standard.

B. IEEE 1901

IEEE 1901 is a standard for high-speed communication via electric power lines. Powerline communication (PLC) is most commonly used to extend Ethernet capabilities using the already existent power infrastructure in a building.

It is already in use in some electric vehicle charging systems, and it is seen as a potential alternative to UTP-based Ethernet for next-generation communication architectures. It combines communication and power cables, which means large savings in space required to route cables through the vehicle.

Strobl *et al.* [40] provided an introduction to the implementation of PLC in an automotive setting, implementing an automotive network using SIG60 PLC transceivers. This implementation seeks to replace low-bandwidth networks such as LIN and operates at 115.2 kb/s. The system implements a master–slave-type network and is quite basic in operation, allowing a single frame on the bus per cycle to ensure collision avoidance. However, for certain applications where cabling space may be at an absolute premium, a PLC network could potentially extend an Ethernet network via powerlines.

Nouvel *et al.* have published a number of papers in the domain of PLC for automotive applications [41]–[45]. Of these papers, [44] provided a detailed analysis of the potential PLC standards that have been investigated for use in automotive scenarios, as well as EMC results and comparisons. Nouvel *et al.* concluded, similar to Strobl *et al.*, that PLC in automotive environments, while not suitable as an end-to-end solution, may be useful in scenarios where cabling space and costs are severely restricted. In [43], a commercial PLC-based solution

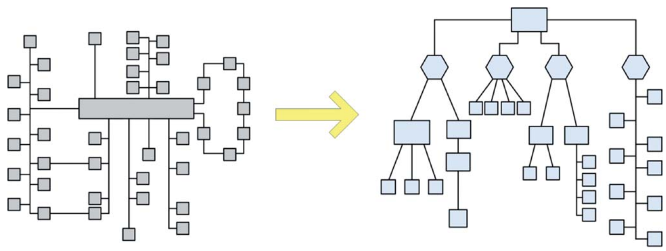

Fig. 4. Migration from heterogeneous architecture to future top-down approach [38].

was created and tested, concluding that it provides throughput that exceeds that of the FlexRay protocol.

C. Topologies

Although it is clear that Ethernet has the potential to provide a large number of benefits to in-vehicle networks, the question of how to network the devices within the vehicle together remains.

Automotive devices are generally split into different functional domains; this involves grouping applications and sensors together into subdomains by functionality or by physical location. As mentioned in Section I, existing networks have organically developed and display significant heterogeneity. CAN may be used for body control data, FlexRay for safety-critical applications, LIN for small serial control messages, and MOST for infotainment data. This variety of different networks leads to difficult-to-maintain inflexible combinations of protocols and topologies. An illustration of this configuration can be seen in Fig. 4. On the left side in Fig. 4 is an example of this type of complex multitechnology network.

To rectify this undesirable situation, a top-down designed approach is required. Lim *et al.* [46] proposed that each of the separate domain within the vehicle reports to a master ECU, which then facilitates interdomain communication, abstracting the detail of each individual network from the Ethernet network backbone. This approach is also proposed by Hank *et al.* [38], and an example of such a network is illustrated on the right side in Fig. 4.

V. Link Layer Protocol

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. However, Ethernet in its default configuration does not provide deterministic or real-time functionality, which is required of the automotive domain. Contemporary Ethernet networks generally utilize transmission control protocol/Internet protocol (IP) to ensure delivery of packets; however, this would not be suitable for a safety-critical automotive environment as it does not provide maximum delay guarantees.

Network communication can very generally be split into two types: event triggered and time triggered. Traffic latencies within an event-triggered network can be probabilistically modeled based on network parameters, whereas those in a time-triggered systems are fixed. Ethernet and CAN both are event-triggered network protocols, whereas FlexRay is time triggered. Both time- and event-triggered traffic exist on current automotive networks, which is a motivating factor behind the use of multiple networking technologies in a single vehicle. In order for Ethernet to provide a unified automotive network backbone, it must be modified to support deterministic delivery of safety-critical traffic.

This means that, without modification, for certain safety-critical applications such as drive by wire, Ethernet cannot be used as it cannot guarantee deterministic behavior.

There are a number of proposed approaches to overcome this problem in the automotive domain; three are most commonly found in the literature: IEEE 802.1Q, AVB Ethernet, and TTEthernet.

A. IEEE 802.1Q VLAN Tagging

IEEE 802.1Q is a simple technique that is used to priority tag packets in an Ethernet network. Although intended for use in tagging packets in virtual LANs (VLANs), it has been used in a number of literature publications in automotive systems [47]–[50]. IEEE 802.1Q operates by adding an extra field to the Ethernet header of a packet, which allows for a priority value to be stored in a 3-bit field, thus supporting eight (2^3) priority levels. When used with a traffic queuing algorithm such as weighted fair queuing, it can function as a lightweight QoS algorithm.

Rahmani *et al.* [48] used 802.1Q tagging to compare the performance of ring and double-star network topologies, concluding that the double-star configuration is more resource efficient and flexible than a unidirectional ring topology. Lim *et al.* [47] provided a performance comparison of IEEE 802.1Q and IEEE AVB, which is explored in more detail in Section V-B2. Although the use of 802.1Q (in the automotive environment) is declining in the literature in favor of the more complex AVB, it has been shown to provide a lightweight, widely supported, and reliable method to improve the QoS of automotive networks.

Lee and Park [51] proposed an 802.1Q-based system, which has been shown to meet even hard real-time delay constraints, with no modification to the network stack or protocols. This method relies on limiting the maximum transmission unit (MTU) of messages that have the same destination as hard real-time messages. They show through both simulation and mathematical analysis that this can be used to provide real-time guarantees to traffic in an 802.1Q-based network. On set up, a bootstrapping approach is taken, whereby each application requests resources, and the network calculates and sets the maximum MTU so that the required delays are met.

B. AVB

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;
- IEEE 802.1Qat: Stream Reservation Protocol (SRP);

- IEEE 802.1Qav: Forwarding and Queuing for Time-Sensitive Streams;
- 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. IEEE 802.1AS utilizes the IEEE 1588 Precision Time Protocol standard to allow for precise time synchronization between nodes. This involves the use of a grandmaster node, which communicates timing information to all the other nodes on the network.

IEEE 802.1Qav handles priority allocation of streams by adding data to the Ethernet header in a very similar way to the 802.1Q standard detailed in Section V-A. In this sense, AVB can be seen to encapsulate the functionality of IEEE 802.1Q while adding more features, at the expense of less universal hardware support and a more complex system.

Streams within an Ethernet AVB capable network can reserve bandwidth using the 802.1Qat standard, by issuing an SRP message. Resources are then allocated at both stream end nodes, and each of the transmit nodes along the path at the link layer (or Level 2) of the OSI model. An important and useful feature of AVB, which is absent from TTEthernet, is online stream reservation. TTEthernet requires stream reservation to be carried out offline.

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 2 ms. *Class B* provides delay guarantees of 50 ms and is mapped to 802.1Q priority level 2 [52].

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 realized. 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 enhancements to facilitate automotive, industrial, and consumer requirements. A number of tier-1 automotive manufacturers and component manufacturers [8] support these operations and the development of associated IEEE standards. The proposed improvements include preemption, which would mitigate the problem of head-of-line blocking (HoLB), a topic explored in more detail in Section V-B1 below.

1) Aeronautical and Industrial Applications: Imtiaz *et al.* [53] carried out a performance study of the suitability of AVB technology for industrial applications, comparing AVB with 802.3 Ethernet and 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 concluded that, for the particular simulation scenario tested, AVB does not offer advantages over 802.3 Ethernet.

In [54], the same authors proposed a method to overcome the effects of HoLB 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 proposed 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.* [55] 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 regard to its use in the automotive domain [47], [56], [57]. In [47], the authors provided 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 prioritization outperforming AVB for the transmission of control data within the vehicle, when that control data are assigned the highest 802.1Q priority value and are 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.

Alderisi *et al.* [58] found that AVB functioned very well for a double-star automotive network containing camera, infotainment, and ADAS application traffic. For workloads up to $\sim$90 Mb/s, jitter and latency values were found to meet the automotive requirements as described in [59].

Work to ensure the suitability of AVB in a harsh automotive environment has been carried out by Kern *et al.* [60]. The authors performed tests on a simple prototype network to ensure that AVB-capable devices perform as expected under varying automotive temperature conditions. The authors concluded that temperatures between -10°C and $+70^\circ$C do not cause problems for AVB-capable consumer devices.

In [52], Zinner *et al.* addressed 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 [52], the authors proposed a system to translate the QoS guarantees provided by MOST and FlexRay to an AVB network, while crucially also maintaining synchronization 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) Theoretical 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, more formal mathematical explorations of the technology are

TABLE II
AUTOMOTIVE NETWORK TRAFFIC TIMING REQUIREMENTS

	Priority Algorithm			Method			
Author	802.1Q	AVB	TTEthernet	Simulation	Prototype	Analytical	Topologies
Lim et al. [56]				✓			Double Star
Lim et al. [64]	✓			✓			Star, Daisy Chain, Tree
Lim et al. [47]	✓	✓		✓			Daisy Chain
Lim et al. [57]		✓		✓			Daisy Chain
Lee et al. [51]	✓			✓			Double Star
Rahmani et al. [50][48]	✓			✓			Double Star, Ring
Steinbach et al. [65]			✓	✓			Star
Steinbach et al. [66]		✓	✓	✓			Tree
Alderisi et al. [58]		✓		✓			Double Star
Alderisi et al. [67]		✓	✓	✓			Star, Double Star
Tuohy et al. [68]				✓			Star
Bartols et al. [69]			✓		✓		Point to Point
Steffen et al. [70]	✓				✓		Daisy Chain
Muller et al. [71]			✓		✓		Point to Point
Diemer et al. [61]		✓				✓	Multistar
Queck et al. [62]		✓				✓	Double Star

also important. Work of this nature can be also found in the literature.

Diemer and Rox [61] provided 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 [62], Queck provided an analysis of the AVB standard through the application of network calculus [63]. In this paper, 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 three traffic classes (see Table II). The authors conclude that, under the assumptions made in deriving the worst case analysis, AVB, and, specifically, 802.1Qav as a queuing paradigm, meet the timing requirements of automotive traffic.

C. TTEthernet

TTEthernet [72], which was first presented by Kopetz *et al.* [73]–[75], 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 60 μs, on top of the existing 802.3 Ethernet.

TTEthernet supports three different traffic types, namely, time triggered (TT), rate constrained (RC), and best effort (BE). TT traffic takes priority over all other types, whereas 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 V-B1 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 [76] 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.* [77] 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.* [78], closely validate the mathematically demonstrated results from [77].

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

VI. IMPLEMENTATIONS

Due to the competitive nature of the automotive industry, it is perhaps unsurprising that details on prototype implementations of the technologies described in Section V are difficult to find. However, there are a number of sources in the literature that detail prototype systems.

Steffen *et al.* [70] and Rahmani [80] detailed a prototype system built in a BMW 530d vehicle, which utilizes the 802.1Q priority scheduling algorithm. This prototype includes two Ethernet switches and a head unit connected in a daisy chain topology. Devices connected to the switches include engine

TABLE III
INTRA-VEHICLE LINK LAYER NETWORKING PAPER COMPARISON

Traffic Class	Max End-to-End Delay	Service Rate
Control Data	2.5ms[70]	10 - 100ms
Safety Data (Video)	45ms[50]	0.05 - 1ms
Infotainment Data	150ms [79]	∼1ms

control modules connected via a CAN—IP gateway, an IP-enabled camera module, a 3G mobile data network connection, a WiFi access point, and an audio/video server operating using Universal Plug and Play. The prototype system was found to work well, including the bridging of CAN traffic onto an IP network, although exact test details and metrics are not included in the publication.

In [69], Bartols *et al.* analyzed the performance of TTEthernet using commercially available hardware, a basic network topology, and a TTTech-developed TTEthernet protocol stack. The results of this real-world testing showed latency values when using a TTEthernet switch were much more stable than those obtained when using an 802.3 Ethernet solution.

Muller *et al.* [71] provided details on an implementation of a TTEthernet-based platform for automotive applications. The system is not as complex as that detailed in [70] and consists of three prototype TTEthernet nodes, created using an ARM-based system on a chip and a traffic generator. The platform was tested under a variety of different traffic load scenarios and was found to reliably operate with all TTEthernet deadlines met for both RC and TT traffic. While this system is more basic than any real automotive implementation with fewer nodes, it does show that TTEthernet represents a viable technology for deterministic in-vehicle networks.

Table III provides a summary breakdown of the papers discussed here and is intended to allow the reader to easily reference and locate all papers corresponding to a particular subject found in the literature.

VII. MIDDLEWARE

The use of Ethernet in vehicles allows for more interoperable compatible networks. Tier-1 manufacturers can easily switch component suppliers provided that all manufacturers use Ethernet as a common communication bus.

However, for the most part, the advanced applications that are made possible by high-bandwidth automotive networks operate on proprietary software stacks. This means that they can require extensive porting or rewriting for new architectures, chipsets, and hardware revisions.

AUtomotive Open System ARchitecture (AUTOSAR) [81] is an industry-led proposed solution to these issues. It consists of a partnership of automotive companies and component manufacturers, including BMW, Daimler, Toyota, GM, Ford, Volkswagen, Volvo, Renault, Hyundai, Honda, and Mitsubishi.

AUTOSAR seeks to provide a common scalable middleware interface between applications and automotive ECUs. This allows for much easier interoperability between vehicle models and even between manufacturers. AUTOSAR provides a method whereby the specific hardware implementation is abstracted from the application developer, allowing for more rapid and generalized development [82]. Some of the basic concepts underlying the AUTOSAR specification are explained in more detail in [83].

The use of AUTOSAR allows for the abstraction of ECU functionality into a middleware layer. The use of a common middleware framework means that applications can be developed once and deployed multiple times, thus saving development time and alleviating complexity.

In addition, the standard seeks to make the creation of automotive applications quicker and more efficient, by allowing developers to use standardized higher level development tools.

Kum *et al.* [84] discussed approaches whereby existing automotive applications and functionality can be migrated to the AUTOSAR platform. Hermans *et al.* [85] provided a case study for the integration of AUTOSAR into the development of an automotive ABS application. The authors found that the use of AUTOSAR did not negatively affect the development process and did not necessitate changes to legacy testing methodologies.

There is much research in the literature concerning the integration of AUTOSAR development into existent testing and embedded development work flows [86]–[89]. There are also a number of papers examining the underlying timing and scheduling performance of the platform, such as [90] and [91].

It is clear from the depth of testing and analysis of the platform in the literature, as well as the near-universal membership of the AUTOSAR partnership by automotive manufacturers and suppliers, that it very likely represents the future of the development of automotive applications.

VIII. DISCUSSION

The preceding sections provide an overview of the current state of in-vehicle automotive networking. This area can often be overlooked by networking researchers, with areas such as vehicle-to-infrastructure and vehicle-to-vehicle communications often seen as more interesting. However, these networks all must interface with the in-vehicle network, and thus, it provides the backbone for all next-generation automotive applications.

It is becoming more and more clear that Ethernet will provide the backbone for the next generation of in-vehicle networks. All major automotive manufacturers belong to one or more special interest/working groups that promote the use of Ethernet in the next generation of vehicles (OPENSIG, AVnu, JasPar, etc.). The development and standardization of QoS mechanisms such as TTEthernet and IEEE AVB provide reliable tools for the development high-speed, safe, and deterministic in-vehicle Ethernet networks. The ongoing development of AVB version 2 and the formation of the IEEE RTPGE Study Group point to steadily increasing demand for automotive-grade Ethernet solutions.

Many questions have been already answered as to the suitability of Ethernet in vehicles, as demonstrated throughout this review paper. Primarily, these center around a number of discrete areas.

1. Selection of PHY Medium

The Ethernet PHY is not suitable for direct deployment in a commercial vehicle, mostly due to space and potential EMC issues. This has led to the development of UTP solutions such as Ethernet PHY Broadcom's Broad-R-Reach system [38], which meet the more stringent automotive EMC requirements [37].

This has also led to the formation of the IEEE RTPGE, which will allow gigabit operation using a physical interface of less than three twisted pairs copper cabling.

Although there are potential alternatives such as Firewire, PLC, and wireless communication, Ethernet has assumed a dominant position over these technologies. Since Ethernet is a widely used and recognized IEEE standard, the automotive industry will benefit from its continued evolution and improvement.

However, the development of the IEEE RTPGE Working Group is in the early stages, and it will be a number of years before commercial vendors will produce hardware that is suitable for gigabit Ethernet deployment in vehicles.

2. Suitability of Link Layer Protocols

It is in the area of link layer protocols that much of the research of in-vehicle networks in the literature has taken place. There are a number of competing approaches, and it is currently somewhat unclear as to which direction the automotive industry will progress. AVB and TTEthernet have both been shown to be viable protocols for use in an in-vehicle network. IEEE 802.1Q has been demonstrated to be a workable solution, but it does not meet automotive requirements under certain conditions.

Although the choice to use Ethernet-based technologies for the next generation of in-vehicle networks appears to have been made by many manufacturers, uncertainty arises as to the nature of the protocols used to guarantee deterministic performance. AVB and TTEthernet meet these requirements; however, they are competing standards and are not mutually compatible. They require manufacturers to commit to one or the other as, in order to use either standard, all nodes on the network must be AVB/TTEthernet aware.

A competitive simulation-based analysis of AVB and TTEthernet carried out by Steinbach *et al.* [66] shows that both technologies provide comparable results in the delivery of time-sensitive automotive traffic (similarly, Alderisi *et al.* [67] carried out a comparison of AVB and TTEthernet, with the same conclusions as found in [66]). Although AVB is shown to be affected more than TTEthernet by cross traffic on the network, it offers advantages in the reliable streaming of multimedia data.

Given that there is little difference between the two standards in terms of performance, we must use other metrics to judge the suitability of one technology over the other. We propose that AVB offers the better solution for the timely delivery of automotive traffic for next-generation wired Ethernet networks for a number of reasons demonstrated in this paper: the volume of supporting work for AVB in the literature, the membership of several tier-1 automotive manufacturers in the AVnu alliance, IEEE support and the development of AVB version 2, which caters more to automotive requirements, and, lastly, the advantages for streaming media provided by AVB, as shown in [66]. The vast majority of the bandwidth used by a next-generation automotive network will be consumed by multimedia, either infotainment or active computer-vision-based safety systems, and it is thus advantageous to use AVB.

There is the potential, as mentioned in [67], for the coexistence of AVB and TTethernet in a single vehicle. In this scenario, each technology would handle different classes of traffic on the network, with AVB focusing on infotainment and video-based ADAS, whereas TTEthernet handles lower level safety-critical applications. This is an interesting possibility, and it would take advantage of the strengths of each technology, but it may cause fragmentation and complexity similar to what we currently see in CAN-, FlexRay-, MOST-, LVDS-, and LIN-based networks. However, since the underlying physical communication medium is the same, i.e., Ethernet, the introduction of hybrid switches or components that support both standards may potentially make this a viable and cost-effective possibility.

There are as yet open questions in relation to these technologies. As shown in Table III, much of the research available in the literature details simulation verification. There are comparatively few papers that detail real-world implementations of the technologies. This may be influenced by the fact that the creation of a real-world test environment involves considerable investment in hardware and is often facilitated through support from automotive manufacturers who may be unwilling to release technical implementation details due to the competitive nature of the automotive industry.

3. Software Platform

The first technical team exploring the possibilities of a common automotive industry standard architecture formed in 2002. AUTOSAR has been steadily developing for a number of years. Although, ostensibly, progress is slow, it has been continuous, measured, and thoroughly documented. Each automotive manufacturer has proprietary specialized platforms that have organically developed over the course of many years; thus, migration to a standard architecture is a gradual process. AUTOSAR reports that a number of manufacturers have already migrated to fully compliant AUTOSAR Basic Software, and most core partners (Daimler, BMW, Peugeot Citroen, Toyota, etc.) will have finished their migration by 2016. The stated goal of the AUTOSAR alliance is to enable innovation by providing a common architecture, and in the coming years, this will allow for greater innovation, interoperability, and cooperation between manufacturers.

IX. Conclusion

It is clear from the body of work in the literature and significant industry interest through groups such as AVnu and OPEN-SIG 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 recognized IEEE standard, the automotive industry will benefit from its continued evolution and improvement.

It is likely that the shift toward fully Ethernet-based automotive networks will be evolutionary and not revolutionary. It is not currently feasible to replace all 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 it becomes cost effective to migrate to a full end-to-end Ethernet solution.

The body of research analyzed in this paper points toward a single conclusion: As automotive networks become more complex, standardization of approaches becomes more and more appealing to manufacturers. This is happening at all levels of the automotive communication stack and is gaining momentum, with organizations such as IEEE RTPGE, OPENSIG, the AVnu alliance, and AUTOSAR coordinating an industry-led push toward extensible and cost-effective standards that will drive the development of in-vehicle networks.

This paper has presented evidence that, as in-vehicle technology becomes more and more complex, there is a drive to standardize approaches across the industry, allowing manufacturers to focus on innovating with exciting applications built on similar foundations. This provides an excellent 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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Shane Tuohy received the B.E. (Hons.) degree in electronic and computer engineering in 2010 from National University of Ireland, Galway (NUIG), Galway, Ireland, where he is currently working toward the Ph.D. degree with the Connaught Automotive Research Group.

His research interests include next-generation automotive communication networks centered around Ethernet implementations, automotive image quality, and network simulation.

Martin Glavin (M'95) received the Diploma and Honors degrees in electronic engineering and the Ph.D. degree in advanced equalization techniques for high-speed digital communications from National University of Ireland (NUI), Galway, Ireland, in 1994, 1997, and 2004, respectively.

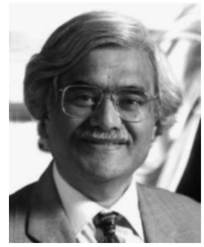
Since 1999 he has been a Lecturer with the Department of Electrical and Electronic Engineering, NUI Galway. His research interests include image processing and embedded systems in the areas of automotive systems and biomedical signal processing.

Ciarán Hughes received the B.E. degree in electronic and computer engineering in 2003 and the Ph.D. degree in 2009 from National University of Ireland (NUI), Galway, Ireland.

In 2003 he was with Connaught Electronics Ltd., Galway [now Valeo Vision Systems (VVS), cosponsors of his Ph.D. research] on field-programmable gate array development of both video and radar systems. His Ph.D. research was in the area of the calibration of fish-eye cameras for application in close-range vision systems for the automotive market. Through his doctoral research, he has been involved in design and image quality aspects for automotive vision system projects with VVS, where he has been employed as a Vision Systems Specialist with the Vision Systems Group since completing his Ph.D. research in 2009.

Edward Jones (M'91) received the B.E. and Ph.D. degrees in electronic engineering from National University of Ireland (NUI), Galway, Ireland.

He has previously been with Toucan Technology Ltd., Dublin, Ireland, and PMC-Sierra, Inc., Sunnyvale, CA, USA, developing digital signal processing (DSP) algorithms for digital-subscriber-line modems. From 2001 to 2002 he was a Senior DSP Architect with Innovada Ltd., developing software for embedded voice-band modem technology. From 2002 to 2003 he was with Duolog Technologies Ltd., where he developed DSP algorithms and implementations for wireless networking systems (including wireless local area networks). He is currently a Lecturer with the Department of Electrical and Electronic Engineering, NUI Galway. His research interests are DSP algorithm development for applications in image processing, speech processing, and biomedical engineering.



Mohan Trivedi (F'09) received the B.E. (Hons.) degree from Birla Institute of Technology and Science, Pilani, India, and the Ph.D. degree from Utah State University, Logan, UT, USA.

He is a Professor of electrical and computer engineering and the Founding Director of the Computer Vision and Robotics Research Laboratory at the University of California, San Diego, La Jolla, CA, USA. He and his team are currently working toward research in machine and human perception, machine learning, distributed video systems, multimodal effect and gesture analysis, human-centered interfaces, and intelligent driver assistance systems. He regularly serves as a Consultant to industry and government agencies in the U.S. and abroad. He has given over 65 keynote/plenary talks.

Dr. Trivedi is a Fellow of The International Association for Pattern Recognition and The International Society for Optical Engineers. He has served as the Editor-in-Chief of the Machine Vision and Applications journal and is currently an Editor of IEEE TRANSACTIONS ON INTELLIGENT TRANSPORTATION SYSTEMS and *Image and Vision Computing*. He was the General Chair for the IEEE Intelligent Vehicles Symposium 2010. His team designed and deployed the Eagle Eyes system on the U.S.–Mexico border in 2006. He was a Charter Member and the Vice Chair of the Executive Committee of the University of California (UC) system-wide UC Discovery Program and as an Expert Panelist for the Strategic Highway Research Program of the Transportation Research Board of the National Academies. He has received the Distinguished Alumnus Award from Utah State University, the Pioneer Award and the Meritorious Service Award from the IEEE Computer Society, and several Best Paper awards.

Liam Kilmartin (M'97) received the B.E. and M.Eng.Sc. degrees in electronic engineering from National University of Ireland, Galway, Ireland, in 1990 and 1994, respectively.

Since 1994 he has been a Lecturer with the Department of Electrical and Electronic Engineering, National University of Ireland. His research interests are focused on the use of signal processing, machine learning and modeling techniques in communication, and biomedical application domain.