Automotive Communications - Past, Current and Future

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Abstract

This paper presents a state-of-practice (SOP) overview of automotive communication technologies, including the latest technology developments. These networking technologies are classified in four major groups: (1) current wired, (2) multimedia, (3) upcoming wired and (4) wireless. Within these groups a few technologies stand out as strong candidates for future automotive networks. The goal of this paper is to give an overview of automotive applications relying on communications, identify the key networking technologies used in various automotive applications, present their properties and attributes, and indicate future challenges in the area of automotive communications.

1 Introduction

Automotive systems are nowadays complex distributed computer systems with various demands on networking capabilities. Most automakers share common subcontractors, and in a modern automotive system more and more applications (subsystems) developed by different subcontractors are required to interact. Advanced subsystem functionalities, such as Vehicle Dynamics Control (VDC), need support for distributed coordinated actions. X-by-wire systems need to be at least as reliable as the systems they are replacing. Moreover, regulations requiring emissions diagnostics together with the ever increasing in-car electronics further increase the number of applications relying on communications. Different automotive applications have different requirements on the networking capabilities, resulting in a number of networking protocols.

An automotive subsystem consists of one or more Electronic Control Units (ECUs). An automotive system consisting of several subsystems with a total of up to 70 ECUs that together might have to distribute more than 2500 variables and signals [28, 34]. This makes the automotive system complex in many ways, including networking. To manage this complexity, and to support the automotive systems of tomorrow, the automotive industry has in recent years set up several large consortia in order to agree on a common scalable electric/electronic architecture (e.g., AUTOSAR [1]) and a common scalable communication system (e.g., FlexRay [17]). As a next step most hydraulic automotive subsystems, such as steering and braking, will be replaced by communication networks (wires) and electric/electromagnetic sensors and actuators. These new solutions are commonly called x-by-wire systems, introducing more requirements on the communication technologies.

The requirements of an automotive communication network origin from the applications and subsystems it has to support. A good overview of automotive architectures and application requirements can be found in [3]. Major automotive subsystems that rely on networking are relevant to chassis, air-bag, powertrain, body and comfort electronics, diagnostics, x-by-wire, multimedia and infotainment, and wireless and telematics. Today several different networking technologies are used to address the various communication requirements set by these subsystems. To interconnect these systems there is a need for high bandwidth together with flexibility and determinism. Also, many subsystems are safety-critical. A big issue that automotive industry has to deal with is the high number of existing networking technologies. From an engineering perspective, it is therefore desirable to move from using many technologies to use fewer and more general ones. To reduce the complexity it is desirable to commit on a set of networking technologies that can be used in most of the applications typically found in an automotive system. In order to support the automotive systems of tomorrow, these networking technologies need to be interconnected. This interconnection should provide timeliness, composability and fault tolerance across the whole "network of networks".

The purpose of this paper is to provide an overview of the different automotive network technologies used today, identifying their key applications, their strengths and possible weaknesses. The networking technologies are classified in four groups based on where their major applications are found: (1) current wired, (2) multimedia, (3) upcoming wired and (4) wireless. Within these groups a few technologies stand out as strong candidates for future automotive systems. Interconnecting these networking technologies also require an efficient middleware. However, addressing this aspect goes beyond the scope of this paper. Interested readers may refer to [34].

This paper is outlined as follows. Section 2 presents an overview of automotive systems, while in Section 3 current wired and multimedia networking technologies are presented, and in Section 4 upcoming wired and wireless networking technologies are presented. All technologies are summarised and discussed in Section 5 and the paper is concluded in Section 6.

2 Automotive systems

A modern car (automotive system) contains a lot of electronic devices (subsystems) such as advanced safety systems, powertrain control, sensors, and means for diagnostics. These subsystems have evolved over time, relying on various communication services provided by different networking technologies.

2.1 Historical perspective

All automotive subsystems were initially connected by dedicated cables. Steering and braking was done using hydraulics and mechanics. However, as automotive systems became more complex, new engineering solutions were to be found.

As the number of automotive subsystems relying on electronics increased, so were the cabling required for their interconnection. To reduce the amount of cabling the concept of fieldbuses was introduced. A fieldbus is serial bus allowing message exchange between nodes connected to the fieldbus. Using a fieldbus, several previously dedicated cables are replaced by a serial bus interconnecting the ECUs, decreasing both weight and cost of the automotive system. Today most ECUs exchange information (communicate) with each other using fieldbuses. The introduction of ECUs, computers, has lead to more advanced automotive subsystems.

Sharing a fieldbus, the amount of cabling in automotive systems is drastically reduced. To incorporate fieldbuses in automotive subsystems the automotive vendors (the car manufacturing companies) initially developed their own fieldbus technologies. However, as many of the automotive vendors share subcontractors there was a need for standardisations. One technology that was standardised in the beginning of the 90ies was the Controller Area Network [23], and it soon became the most used fieldbus in the automotive industry. Due to its popularity, and that CAN only comprise layer 1+2 of the OSI layers, several higher layer protocols have been developed on top of CAN over the years, for example, CAN Kingdom [9], CANopen [13] and DeviceNet [16]. These higher layer protocols simplify the usage of CAN in terms of, e.g., development and maintenance, by their capabilities and tool support.

However, as the most recent technology advances push for replacing hydraulic parts of automotive systems, such as steering and braking, with electronics, there is an industrial need for new reliable high-speed fieldbus networks. Such fieldbuses have been developed and shown to work in several prototype cars. These new "by-wire" solutions are commonly called *x-by-wire systems*. There are several reasons for the automotive producers willing to replace hydraulics and mechanics with electronics. Maybe the most important reasons are cost and the technological limitation of hydraulic systems. Implementing new more advanced functionality using hydraulics will be too complicated. Moreover, hydraulic systems are somewhat hard to work with since they involve fluids and pipes. They also cost a lot and they are not very environmentally friendly, especially when a car is to be recycled.

2.2 Communication requirements

The requirements on automotive communications very much depend on the subsystems using the automotive network. Today several different fieldbus technologies are used to address various communication requirements, which include fault tolerance, determinism, bandwidth, flexibility and security.

• **Fault tolerance -** When the system does not behave as its specification it is caused by faults, errors and failures [2]. When a failure occurs, this is caused by an error in the system. An error is an unintended state, or part of a state, of the system. The cause of an error is a fault. Hence, a fault can cause an error which might result in a failure.

Fault tolerant (typically safety-critical) communication systems are built so they are tolerant to defective circuits, line failures etc., and constructed using redundant hard- and software architectures. Moreover, they should provide error containment, by using, for example, bus guardians to prevent the existence of babbling idiots [7].

• **Determinism -** A deterministic communication system provides guarantees in terms of timeliness, i.e., it makes it possible to know the transmission time of a message. Deterministic communication requires correct reception of messages. Many safety-critical automotive systems and subsystems also have strong real-time requirements which need determinism, i.e. messages have to be sent at predefined time instants (or within precise time intervals) to fulfil the intended subsystem functionality. An example is an airbag system, as the airbag has to be inflated at exactly the correct time in order to function properly, not too early nor too late.

• **Bandwidth -** High bandwidth is also required in many automotive subsystems. However, there is a trade-off between required bandwidth, the cost of providing such a bandwidth and the level of subsystem integration that is possible to achieve with a single shared communication bus. In many cases it is more desirable selecting a cheaper communication bus with lower bandwidth due to strong requirements on cost. However, the latest automotive communication technologies provide high bandwidth allowing for the latest automotive subsystems working together with high degree of system integration.

• **Flexibility -** Flexibility can be seen as, for example, the ability to handle event- and time-triggered messages, the possibility to cope with varying load and/or number of message flows on the network, scalability and extensibility of the network. In Time Division Multiple Access (TDMA) networks, all message transmissions must be predetermined offline, while in Carrier Sense Multiple Access (CDMA) networks message transmissions are resolved online. The latter is often considered more flexible than the former. Some networking technologies allow a combination of TDMA and CSMA message transmissions.

• **Security -** When the communication is reachable from outside the automotive system by, e.g., diagnostics tools, wireless connections and telematics, it is important to ensure the security of the system, i.e., no authorized accesses to the system have to be possible [26].

2.3 Typical subsystems

In an automotive system several subsystems rely on networking. Here eight typical types of such automotive subsystems are distinguished:

1. **Chassis systems**, a part of the *vehicle active safety systems*, include *Vehicle Dynamics Control (VDC)*, also known as *Electronic Stability Program (ESP)*. VDC/ESP are designed to assist the driver in over-steering, under-steering and roll-over situations [46]. The *Anti-lock Brake System (ABS)* prevents the wheels from locking in a break situation. This helps the driver to maintain steering ability and avoid skidding during breaking. All these systems require *feedback control*.
2. **Air-bag systems** [6] are a part of the *vehicle passive safety systems*, controlling the operation of air-bags in the vehicle. Typically a vehicle contains several air-bags. These air-bags are connected to sensors that detect abnormal situations, e.g., sudden vehicle acceleration or deacceleration. Once an abnormal situation is detected the appropriate (depending on the type of crash) air-bags are inflated in about half a millisecond after the detection of a crash. Seat-belt pre-tensioners are used to pick up the slack and stretch the safety belt.
3. **Powertrain** is the assembly by which power is transmitted from the engine of the vehicle, through the gearbox, to the driving axis. Powertrain includes *engine control*, which involves the coordination of fuel injection, engine speed, valve control, cam timing etc.
4. **Body and comfort electronics** require *discrete control*. Examples of these subsystems are climate control, cruise control, locks, window lifts, seat control and Human Machine Interfaces (HMI), to mention a few. These systems typically rely on driver interaction and are not safety-critical. They involve hundreds of system states and events and interface to physical components in the vehicle, e.g., motors and switches.
5. **X-by-wire** is the notation for new subsystems replacing hydraulic and mechanical parts with electronics and computer (feedback) control systems. Examples of x-by-wire systems are *steer-by-wire*, *shift-by-wire*, *throttle-by-wire* and *break-by-wire*.
6. **Multimedia and infotainment** systems include for example, car stereos, speakers, GPS, monitors, video games, voice processing, HMI, Internet connectivity etc.
7. **Wireless and telematics** are used for interconnection of wireless devices such as laptop computers, cell phones, and GPS units. Other telematic functions include traffic information, fleet management systems, maintenance systems and anti-theft systems.

Apart from the subsystems listed above, relying on networking, **diagnostics** is required by many vehicle functions such as emissions monitoring (enforced by law in some countries, e.g., OBD [41]), diagnosing of components and properties, service and maintenance with the possibility of downloading and updating software.

The above mentioned automotive subsystems and diagnostics are mapped with the communication requirements presented in Section 2.2. The mapping is presented in Table 1.

	Communication requirements				
Subsystem	Fault-tolerance	Deter-minism	Band-width	Flexib-ility	Secu-rity
Chassis	YES	YES	SOME	NO	NO
Air-bag	YES	YES	SOME	NO	NO
Powertrain	SOME	YES	YES	SOME	NO
Body and comfort	NO	SOME	SOME	YES	NO
X-by-wire	YES	YES	SOME	NO	NO
Multimedia / infotainment	NO	SOME	YES	YES	NO
Wireless / telematics	NO	SOME	SOME	YES	YES
Diagnostics	NO	SOME	NO	YES	YES

Table 1. Automotive subsystems and their major requirements.

3 Automotive communication technologies

This section presents the current state-of-practice (SOP) of automotive communication technologies. The network technologies are classified based on their major usage in two groups: (1) current wired and (2) multimedia. Also, an example automotive system is presented.

3.1 Current wired technologies

Today several fieldbus technologies are used by different automotive system vendors. In this section, three of the most common fieldbus technologies are presented in detail, namely LIN, CAN and Byteflight. Following this, a number of other relevant communication technologies are briefly mentioned.

LIN The Local Interconnect Network (LIN) [29], was initiated 1998 by a consortium of automotive companies (Audi, BMW, Daimler-Chrysler, Volcano, Volvo and Volkswagen) together with Motorola. LIN was standardised (open standard) in 2000 (LIN 1.1) and 2003 (LIN 2.0) and introduced in its first production car series in 2001. Today it holds a strong position in the automotive application domain where it coexists well with CAN.

LIN is an inexpensive network, providing network speeds of up to 20 KBps. LIN is typically used in body and comfort subsystems to control devices such as seat control, light sensors and climate control. For example, one subsystem could be a door of a car with all its functionality such as window lifts, door locks etc. These subsystems are then interconnected using (commonly) the CAN network via a LIN/CAN gateway. LIN is often used together with CAN as LIN complements CAN by being much cheaper and simpler yet providing the communications needed for typical non safety-related automotive subsystems.

CAN The Controller Area Network (CAN) [36], was developed in the beginning of the eighties by Bosch. Today CAN is the most widely used vehicular network in the automotive industry. Over the years several different CAN standards have been developed and used in different applications. The ISO 11898 [23, 24] is the most commonly used fieldbus in the European automotive industry. However, in the US SAE J1850 [37] plays the main role, while in the truck and bus applications J1939 [38] is widely used. J1850 is, however, expected to be phased out and possibly replaced by SAE J2284 [39]. J2284 is based on ISO 11898. There is also a fault tolerant version of CAN, called ISO 11519-2 [22], which is relying on a two wire low speed implementation of CAN. All of these CAN standards work in a similar way and will therefore in this paper be simply referred as CAN from now on. Their major differences are presented in [30]. Differences are mainly in transmission speeds and higher layer protocols as well as the applications in which they are used.

Byteflight Byteflight [4, 8] was introduced by BMW in 1996, and then further developed by BMW, ELMOS, Infineon, Motorola and Tyco EC. The main intended application domain for Byteflight is safety-critical systems, where possibly CAN is used today, but not in the future, as further development will require higher bandwidth. A typical application is an airbag system or seat-belt tensioners with fast response-time requirements and short mission-time. Flexibility, support for event-triggered traffic, and higher bandwidth compared with CAN were the main requirements when Byteflight was developed. Byteflight provides network speeds of up to 10 MBps, and controllers are available off-the-shelf today. Byteflight is used in the automotive domain by, e.g., BMW, and in avionics by Avidyne. Byteflight is a candidate for x-by-wire systems. However, it has been extended to be part of the FlexRay protocol (presented in Section 4.1).

3.1.1 Other technologies

LIN, CAN and Byteflight represent strong technologies with different service possibilities (low, medium and high speed/cost networks), and they are the three more common communication technologies used for chassis, air-bag, powertrain, body and comfort electronics, and diagnostics systems. These are the historically first applications of automotive networking, so many technologies have been used over the years. Some have been persistent whereas others have been phased out. Some of the other more common technologies are:

• **Safe-by-Wire** [6] is a master/slave network mainly used for airbag control. Safe-by-Wire has features taken from CAN and supports communication speeds of 150Kbps. Since CAN and LIN are considered not safe enough for airbag control, the Safe-by-Wire Consortium was formed and developed this communication protocol.

• **Motorola Interconnect (MI)** [33] is similar to LIN in the sense that it is a simple low cost master/slave type of network intended for smart sensors in comfort electronics such as seats, mirrors and window lifts. However, LIN is close to being the world standard in automotive systems today.

• **Distributed Systems Interface (DSI)** [32] is a master/slave network providing communication speeds of up to 150Kbps, intended for safety-related applications such as airbag systems.

3.2 Multimedia

Looking at automotive multimedia and infotainment, MOST, or Media Oriented Systems Transport [31], is the de-facto standard today. Other technologies are, e.g., the D2B used in some Mercedes-Benz models. It is worth noticing that Mercedes is using MOST in some of their more recent models.

MOST To provide communications for multimedia applications, MOST is commonly used. MOST was initiated in 1997, mainly intended as a communications network for automotive multimedia applications and has several supporters such as Audi, BMW and Daimler-Chrysler. Typical MOST applications are the interconnection of multimedia and infotainment such as video displays, GPS navigation, active speakers and digital radios. Today more than 60 companies are using MOST in their products.

3.2.1 Other technologies

The area of multimedia and infotainment initially targeted interconnection of personal computers (PCs) with multimedia devices such as cameras, video recorders and so on. Two of the more common PC interconnection technologies, Firewire and USB, are now evaluated for use in automotive applications as well.

Some of the major automotive networks for multimedia and infotainment, together with MOST, are the following:

• **Domestic Digital Bus (D2B)** [14], by the Optical Chip Consortium. It is a ring/star optic network providing up to 20Mbps communications. D2B is used in some Mercedes-Benz models.

• **Mobile Multimedia Link (MML Bus)** [15] by Delphi Automotive Systems. It is a master/slave optic network providing 100Mbps communications and plug-and-play functionality.

• **IDB-1394 (Automotive Firewire)** [19], originally used to connect PC devices, but also trying to reach the automotive market.

• **USB** [45], as Firewire, originally used in the PC market now trying to reach the automotive market.

3.3 An example automotive system

As an illustration of an automotive computer system, consider the one found in Volvo XC90 as presented in Figure 1[1]. In the figure the networking infrastructure of the XC90 is presented, while a selection of the corresponding ECU explanations is given in Table 2. All "blocks" in the figure represents one ECU.

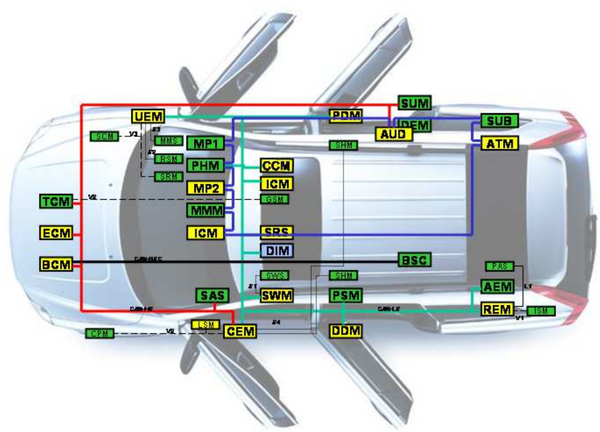

Figure 1. Network infrastructure of Volvo XC90.

Block	Powertrain and chassis	Block	Infotainment (cont')
TCM	Transmission control M	ICM	Infotainment control M
ECM	Engine control M	**Block**	**Body electronics**
BCM	Brake control M	DDM	Driver door M
BSC	Body sensor cluster	REM	Rear electronic M
SAS	Steering angle sensor	PDM	Passenger door M
SUM	Suspension M	CCM	Climate control M
DEM	Differential electronic M	ICM	Infotainment control M
Block	**Infotainment**	UEM	Upper electronic M
AUD	Audio M	DIM	Driver information M
MP1	Media player 1	AEM	Auxiliary electronic M
MP2	Media player 2	SRS	Supplementary restraint system
PHM	Phone module	PSM	Passenger seat M
MMM	Multimedia M	SWM	Steering wheel M
SUB	Subwoofer	CEM	Central electronic M
ATM	Antenna tuner M		

Table 2. ECU explanations of Volvo XC90 (M = module).

The communications is divided into three groups: 1) powertrain and chassis, 2) body electronics, and 3) infotainment. A total of around 40 ECUs are found in the XC90, and the Controller Area Network (CAN) is the most common network used to interconnect these ECUs. Also, the Local Interconnect Network (LIN) is used to connect slave nodes in the system. There are two CAN buses interconnected with each other using a gateway. The gateway is the Central Electronic Module (CEM) in the figure. The two CAN busses have different speeds. One 500Kbps "high speed" CAN network is used for powertrain and chassis, and another 125Kbps "low speed" CAN network is used for body electronics. MOST is used for infotainment.

The XC90 contains many subsystems consisting of a number of ECUs each. However, other car models are known to have close to 100 ECUs. Integrating these subsystems on the communication networks is becoming more and more complicated. In the case of the XC90, Volvo is using the Volcano concept [3, 11]. The Volcano system provides tools for packaging data (signals) into network frames, both for CAN and LIN networks. Using the Volcano tools it is also possible to perform a timing analysis of the system.

[1] Courtesy of Volvo Car Corporation.

4 Upcoming automotive technologies

This section presents the two areas that are getting most attention in automotive communications nowadays: (1) upcoming wired technologies supporting x-by-wire applications, and (2) wireless technologies.

4.1 Wired technologies

As said before, x-by-wire systems need fault-tolerant communication with deterministic message transmissions and low jitter. This is traditionally solved using TDMA protocols, thanks to their deterministic nature. Three of the most common TDMA-based networks for automotive applications are presented in detail, namely TTP, TT-CAN and FlexRay. However, they differ in their fault-tolerant capabilities.

TTP The Time-Triggered Protocol (TTP) is part of the Time-Triggered Architecture (TTA) by TTTech [42, 43]. TTTech provides time-triggered solutions based on more than 20 years of research in the topic. TTP was first introduced in 1994 [27] as a pure TDMA protocol nowadays available in two versions, TTP/A and TTP/C. TTP/A is a master/slave TDMA protocol, whereas TTP/C is a fully distributed TDMA protocol more focused on fault tolerance, and therefore more complex and expensive than TTP/A.

The first TTP off-the-shelf communication controller was released in 1998. However, although being excellent from the safety-critical point of view, TTP/C might probably not be the choice for x-by-wire applications due to limited flexibility and high costs. Conflicting interests between TTP/C and the automotive industry led to the initiation of FlexRay [40] (described below). TTP/C, providing network speeds of up to 25 MBps, is a highly fault tolerant network intended for safety-critical systems such as x-by-wire and avionics. TTP/C implements several fault tolerant mechanisms such as atomic broadcast using membership service, distributed clock synchronisation and bus guardians. TTP/C is very deterministic at the cost of being less flexible compared with, e.g., FlexRay. A valuable property of TTP/C is that it ensures that there can be no single point of failure.

TT-CAN The Time-Triggered CAN (TT-CAN) [12] was introduced 1999 as a time-triggered session layer on top of CAN. TT-CAN is a hybrid TDMA on top of CSMA allowing both time-triggered and event-triggered traffic, which is a key strength of this protocol. TT-CAN is standardised by ISO [25] and intended for x-by-wire systems. However, it does not provide the same level of fault tolerance as TTP and FlexRay, which are the other two candidates for x-by-wire systems.

Strong points of TT-CAN are the support of coexisting event- and time-triggered traffic together with the fact that it is standardised by ISO. It is also on top of standard CAN which allows for an easy transition from CAN to TT-CAN. Moreover, there exist off-the-shelf TT-CAN controllers.

FlexRay In 1998 BMW and Daimler-Chrysler analysed the current available automotive networks (e.g., CAN, TTP, MOST and Byteflight) and found that none of those technologies fulfil the future needs of next generation automotive systems, especially when the automotive industry will take the next step towards x-by-wire.

As a response to this, the FlexRay consortium [17] was formed with the goal to develop a new protocol. FlexRay [18] provides network speeds of up to 10 MBps. This new protocol should be the solution for the introduction of x-by-wire systems as well as the replacement of some of the fieldbuses currently used, thus reducing the total number of in-car different networking technologies. Today basically all car manufacturers have joined this consortium, and in the middle of 2004, the protocol specification was made public.

FlexRay is expected to be the de-facto communication standard for high-speed automotive control applications interconnecting ECUs in future automotive systems. A special area of interest will be high-speed safety-critical automotive systems such as x-by-wire and advanced powertrain applications.

4.2 Wireless technologies

There are several applications pushing for the adoption of wireless communications in automotive systems, both within the vehicle (in-vehicle communications) and between the vehicle and its surroundings (inter-vehicle communications). Looking at in-vehicle communications, more and more portable devices, e.g., mobile phones, portable GSM devices and laptop computers could exploit the possibility of interconnection with the vehicle. Also, several new applications will exploit the possibility of inter-vehicle communications, e.g., vehicle-to-vehicle [10] and vehicle-to-roadside communications.

This paper presents the two more common wireless protocols that might be used in the automotive industry in the near future, namely Bluetooth and ZigBee.

Bluetooth Bluetooth (IEEE 802.15.1) [5, 21] currently provides network speeds of up to 3 Mbps (Bluetooth v2.0). Originally devised for Personal Area Network (PAN) deployment for low-cost, low-power, short-range wireless ad hoc interconnection, Bluetooth technology has fast become very appealing also for the automotive environment, as a potential automotive wireless networking technology.

As a response to this interest, the Bluetooth Special Interest Group (SIG) formed the Car Working Group in December 1999. The Hands-Free profile was the first of several application level specifications expected from the Car Working Group. Using the new Hands-Free profile, products that implement the Bluetooth specification can facilitate automatic establishment of a connection between the car's hands-free system (typically part of its audio system) and a mobile phone.

The Bluetooth SIG, in November 2004, laid out a three-year roadmap for future improvements to Bluetooth. Prioritised targets include Quality of Service (QoS), security, power consumption, multicast capabilities, and privacy enhancements. Long-range performance improvements are expected to increase the range of very low power Bluetooth-enabled sensors to approximately 100 meters.

ZigBee ZigBee (IEEE 802.15.4) [47, 21] is a new low-cost and low-power wireless PAN standard, intended to meet the needs of sensors and control devices. Typical ZigBee applications are monitoring and control applications which do not require high bandwidth, but do impose severe requirements on latency and energy consumption. Despite the number of low data rates proprietary systems designed to fulfil the above mentioned requirements, there were no standards that met them. Moreover, the usage of such legacy systems raised significant interoperability problems which ZigBee technology solves, providing a standardized base set of solutions for sensor and control systems. The ZigBee Alliance (with over 120 company members) ratified the first ZigBee specification for wireless data communications in December 2004.

ZigBee provides network speeds of up to 250 Kbps, and is expected to be largely used in automotive as sensor network for monitoring and control purposes (air conditioning, heating, ventilation, lighting control, etc.).

4.2.1 Other technologies

• **Wi-Fi** Wi-Fi stands for *wireless fidelity* and is the general term for any type of IEEE 802.11 network [20]. Wi-Fi is used for inter-vehicle communications by, e.g., Car2Car Consortium [10], a non-profit organisation initiated by European vehicle manufacturers. Applications here are advanced drive assistance to reduce the number of accidents, decentralized floating car data to improve local traffic flow and efficiency, and user communications and information services for comfort and business applications to driver and passengers. Research projects working in this area are, for example, the European Network-on-Wheels (NoW) project [35].

• **UWB** (IEEE 802.15.3a), or Ultra Wide Band [44, 21], is a potential competitor to the IEEE 802.11 standards, providing speeds of up to hundreds of Mbps and robust communications thanks to its usage of broad spectrum of frequencies. UWB is likely to be used in applications requiring high bandwidth, such as interconnection of multimedia devices. Other potential automotive applications which could be supported by UWB are collision-detection systems and suspension systems that respond to road conditions [44]. However, being UWB a young technology, these applications are not available yet.

5 Summary

As an overview of the automotive communication technologies used today, consider Table 3 that shows which networking technologies that are used in what applications, typical communication requirements provided by these networking technologies, as well as some key properties of each technology.

Looking at current wired networking technologies in the automotive domain, LIN and CAN are the strongest technologies. Also, Byteflight is to some extent used in more safety-critical applications. MOST is the most widely used networking technology for multimedia and infotainment systems.

However, in a modern automotive system there is a need for several communication technologies to co-exist, e.g., both time-triggered and event-triggered traffic have to be supported. CAN is very good in handling event-triggered traffic, and today it is the most widely used wired networking technology. CAN has also been extended with a time-triggered session layer, called TT-CAN, to support time-triggered traffic. However, since TT-CAN relies on the CAN lower layers, it is lacking fault-tolerant mechanisms and bandwidth capabilities. Hence, CAN/TT-CAN is not commonly suggested for future applications, such as x-by-wire. On the other hand, TTP is a highly fault-tolerant network developed and intended for safety-critical systems such as x-by-wire and avionics. TTP is implementing several fault-tolerant mechanisms and ensures that there can be no single point of failure. TTP is very deterministic at the cost of being less flexible in terms of message transmissions compared with, e.g., FlexRay. A drawback with TTP is that due to its somewhat inflexible message transmission and high cost, the use of another fieldbus is needed for other applications in the car where high bandwidth together with event-triggered capabilities is needed.

While TTP does not directly support event-traffic, FlexRay does, as it combines TDMA message transmission and the FTDMA of Byteflight, thus allowing for both time-triggered and event-triggered message transmissions. Moreover, FlexRay was developed with safety-critical applications in mind, just like TTP. Hence, using FlexRay it is possible to develop a wide range of systems, reducing the need for several fieldbus technologies.

Among TT-CAN, TTP, and FlexRay, the latter has the biggest potential for becoming the next generation automotive network for safety-critical fault-tolerant applications, mainly because it is heavily backed up by industrial partners and pushed by most major industrial automakers where several have moved from being TTP-supporters to being FlexRay-supporters [40].

Looking at wireless technologies, Bluetooth is the most widely-used in-car wireless technology today. In a Bluetooth-enabled vehicle, the car audio system takes over the phone function and any Bluetooth device can easily connect to another one (i.e. CD, DVD, MP3 players connect to the car speakers). Moreover, through Bluetooth interfaces, hand-held computers and diagnostic equipments can interface to the car and access services provided by the onboard diagnostic and control systems. The frequency hopping modulation technique is very suitable to harsh environments often found in automotive applications.

On the other hand, in the automotive context, ZigBee, thanks to its low power and low-latency features, is expected to be used in non bandwidth-greedy monitoring and control applications, related to air-conditioning and lighting control, telemetry, vehicle immobilizers, toll collection, vehicle identification, tire tracking/monitoring.

6 Conclusions

This paper has presented a survey of existing and upcoming automotive networking technologies, identifying traditional and novel automotive application requirements and addressing to what extent existent and upcoming networking technologies are able to meet such requirements. The paper has discussed the next steps in automotive communications, with a specific focus on x-by-wire systems and wireless applications. One of the bigger challenges today is interconnecting a modern automotive architecture of possibly heterogeneous networks. This can be achieved by developing standardised middleware technologies.

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	Networking technology group								
	Current wired			**Upcoming wired**			**Multimedia**	**Wireless**	
Usage	LIN	CAN	Byteflight	TTP	TT-CAN	FlexRay	MOST	Bluetooth	ZigBee
Chassis	NO	YES	NO	SOME	YES	NO	NO	NO	NO
Air-bags	NO	YES	YES	NO	NO	NO	NO	NO	NO
Powertrain	NO	YES	YES	SOME	YES	SOME	NO	NO	NO
Body and comfort	YES	YES	NO	NO	NO	NO	NO	NO	YES
X-by-wire	NO	SOME	YES	YES	YES	YES	NO	NO	NO
Multimedia / infotainment	NO	NO	NO	NO	NO	NO	YES	YES	NO
Wireless / Telematics	NO	NO	NO	NO	NO	NO	NO	YES	YES
Diagnostics	SOME	YES	SOME	SOME	SOME	SOME	SOME	YES	YES
Requirement	LIN	CAN	Byteflight	TTP	TT-CAN	FlexRay	MOST	Bluetooth	ZigBee
Fault tolerance	NO	SOME	YES	YES	SOME	YES	NO	NO	NO
Determinism	YES	YES	YES	YES	YES	YES	SOME	SOME	SOME
Bandwidth	NO	SOME	YES	YES	SOME	YES	YES	SOME	SOME
Flexibility	YES	YES	YES	SOME	YES	YES	YES	YES	YES
Security	NO	NO	NO	NO	NO	NO	SOME	YES	YES
Property	LIN	CAN	Byteflight	TTP	TT-CAN	FlexRay	MOST	Bluetooth	ZigBee
Bit rate (max)	20Kbps	1Mbps	10Mbps	25Mbps	1Mbps	10Mbps	25Mbps	3Mbps	250Kbps
Cost (Low, Medium, High)	L	L / M	M	H	L	M	H	H	M

Table 3. Networking technologies: usage, requirements and properties.

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