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A Survey on Vehicular Communication Technologies

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Abstract. Nowadays it is common for vehicles to be equipped, not only with huge computing power, but also with great communication capabilities, materialized in multiple and various wired and wireless interfaces. This paper surveys the most common inter and intra vehicle technologies. First, an introduction to *Intelligent Transportation Systems* and *Vehicle Communication Systems* is presented. Then, the technologies usually found in vehicles are characterized in detail - their advantages and flaws regarding particular communication scenarios are also discussed. Finally, the paper concludes with a mapping between potential wireless communication technologies for the different types of ITS applications.

Keywords. Vehicular Networks, Wired Communication Technologies, Wireless Communication Technologies, V2X

1. Introduction

According to some researches [1] [2], it is expected that global Vehicle-to-X (V2X) modules in new vehicles will reach 62% and that OEM and aftermarket V2X modules will grow to 423 million by 2027. It is expected that vehicles will be able to communicate and exchange important information that can help prevent accidents, save lives, ease traffic flow or even improve the environment. However, and although there are available multiple forms of communication, vehicles still connect mostly to the Internet and through the use of cellular networks, without taking any advantage of the existing solutions. This happens despite the huge research effort in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, as can be verified by the number of publications and standardization initiatives in the area, such as [3] or [4]. In order to keep up with the innovations emerging in the automotive environment, vehicles are forced to advance in hardware and processing power, which is causing electronic systems to become more and more complex and diverse. Due to these progressive advancements, it is quite common to find several tens of *Electronic Controller Units (ECUs)* in high-tech cars and even in low-end cars (embedded in doors, roof, and so on). Sensors and processors are found in different parts of the vehicle and are typically used to provide the driver with information about the surrounding environment.

This paper presents an overview of the most typical vehicular networking technologies. These technologies are analyzed in detail and their potential usefulness for vehicular

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connectivity is also discussed. This work aims to further promote and emphasize the importance of communication technologies in the vehicle environments research. Papers [5–11] focus on similar issues, but with different approaches and perspectives on the subject. Next, Section 2 introduces an overview of Intelligent Transportation Systems (ITS). Section 3 presents a characterizations of wired and wireless networking technologies. All technologies are summarized and discussed in Section 4 and the paper is concluded in Section 5.

2. Intelligent Transportation Systems

ITS is defined by the European Parliament [12] as systems in which information and means of communication are implemented in road transportation (including infrastructures, vehicles, users, traffic and mobility management, and interfaces with other transportation modes). The ITS standards are defined so that one can establish and enable interoperability: specifying who communicates with whom and the messages format, which protocol should be used in which communication media, and so on. ITS potential attracts research communities from different fields to develop Vehicular Ad Hoc Network (VANET) applications, protocols, tools, etc. There are several papers that cover these issues and [13–16] are also important works.

Vehicular Communication Systems (VCS) are networks where vehicles and roadside units work as the communicating nodes to share information with each other. Since VCS use a cooperative approach, accidents and traffic congestion avoidance can become more effective than vehicles solving problems by themselves. The idea of vehicle communication is that vehicles, roadside infrastructures and back-end work together. Vehicle communications bring a lot of benefits to users, such as improved safety and driving experience. The vehicle communications applications that provide these benefits can be divided [9, 17, 18] in three basic categories: safety, mobility and comfort (both considered non-safety). Mobility applications focus in improving traffic flow, resorting to live traffic updates, route guidance, and so on. Comfort applications mean to assure that driving is more pleasant to the user - offering a wide range of functionalities like email, social networking, etc. Safety applications can also be divided in two types: soft safety applications (intended to increase drivers safety but, since they do not require immediate attention, they are less time-critical) and hard safety applications (applications used to prevent accidents or, at least, minimize the damage if the crash is unavoidable).

3. Communication Technologies

Connected vehicles require a very efficient VCS, essentially due to the short delays that this type of connection depends upon (specially when the communication concerns safety applications). The following section describes the main characteristics of the most common communication technologies existent in these systems and inside the vehicles themselves.

3.1. Wired Communication Technologies

Controller Area Network

Controller Area Network (CAN) is a bus standard designed to allow micro-controllers to communicate between them. It consists of a broadcast message-based protocol which efficiently supports distributed real-time control with a very high level of security [19]. It is the most widely used solution in the industry. It is characterized for being robust, simple to configure and to have excellent fault tolerance capabilities. The CAN protocol is defined in the ISO 11898-X set of standards. The ISO 11898-2 standard defines the high speed CAN (the most common standard), with data rates up to 1 Mb/s with a possible bus length of 40m. ISO 11898-3 defines the fault tolerant CAN, with data rates up to 125 Kb/s. It allows the transmission of data asymmetrically over one single bus line in case of an electrical failure in another line. In 2012, Bosch introduced [20] the CAN Flexible Data-rate. This protocol improved the CAN data rate limits, allowing to transmit data faster than 1 Mb/s by changing the payload from 8 bytes up to 64 bytes long.

Local Interconnect Network

The Local Interconnect Network (LIN) [21] is a cost-effective serial communication technology used for interconnecting ECUs with smart sensors and actuators when all the features from CAN are not required. It holds a strong position in the automotive domain since it complements well with the existing solutions. LIN is the enabling factor for the implementation of a hierarchical vehicle networks, in order to further enhance communication quality and reduce vehicles cost. LIN is capable of providing network speeds of up to 20 KB/s. It is based on ISO 9141 and is typically used in the area of comfort subsystems to control devices such as seat control and light sensors. Currently, the LIN specification is being transcribed to the ISO as part of the process to be accepted as the ISO 17987-X standard.

Media Oriented Systems Transport

Media Oriented Systems Transport (MOST) [22] is a high-speed multimedia network technology. It is typically used in the automotive industry for infotainment applications. It defines mechanisms for sending streaming/packet-based data and provides a complete application framework to control interaction between devices. MOST eliminates the need for buffering and sample rate conversion, assuring connection to simple and inexpensive devices. The bandwidth that is assigned for each connection is always available and reserved for the dedicated stream, assuring no interruptions, collisions, or delays in the communication. MOST supports different speed grades and physical layers. Currently, there are three versions available: *MOST 25* (data rate around 25 Mb/s), *MOST 50* (50 Mb/s) and *MOST 150* (150 Mb/s).

FlexRay

In 1998, the available technologies were not able to fulfill the future needs of automotive systems. Hence, the FlexRay consortium was created. Its goal was to develop a protocol that allowed the installation of x-by-wire systems and also the replacement of solutions that were used at the time (reducing the number of in-vehicle different networking technologies). FlexRay [23] delivers the requirements for x-by-wire applications (e.g. drive-by-wire). FlexRay is still available as a set of ISO standards: ISO 17458-X. FlexRay provides data rates up to 10 Mb/s, supports both star and passive bus topologies and can have two independent data channels that are used for fault-tolerance. However, FlexRay has disadvantages such its lower operating voltage levels and its asymmetry of the edges - which leads to problems when the network length is extended.

Ethernet

Ethernet [24] is a very well-known technology and it is the most widely installed local area network technology (chosen due to its speed, flexibility and cost). Typical automotive technologies have a clear advantage in comparison to Ethernet solutions - they were designed with in-vehicle communication in mind and the bandwidth levels provided at the time of the specifications development were sufficient for the applications that they supported. However, nowadays this is no longer the case - the main motivation for using Ethernet in vehicles is indeed the increased bandwidth it can offer. Ethernet implementation in new vehicles is expected to grow to 40% in 2020 [25]. The BroadR-Reach Ethernet standard [26] was created by the OPEN (One-Pair Ether-Net) alliance and it specifies a physical layer operating full-duplex over one pair of UTP cables at 100 Mb/s, allowing multiple in-vehicle systems to access information over a single cable simultaneously. This solution eliminates the manufacturers need for expensive cabling and it also significantly reduces the cabling weight. This Ethernet technology is engineered to meet the picky requirements of in-vehicle communication and it is optimized for simultaneous applications. IEEE acknowledge Ethernet's importance in vehicles and defined the P802.3bw standard [27]. However, and as the automotive corporations realize that although 100 Mb/s is enough for media transmission, it is not enough to act as a backbone in a vehicle. Thus, a new IEEE task force was created to address this problem. The IEEE 802.3bp task force is an effort to define the IEEE 802.3bp standard, which aims for automotive Ethernet at 1 Gb/s.

3.2. Wireless Communication Technologies

Bluetooth

Bluetooth wireless technology is a short-range communications system intended to replace the cable(s) connecting portable and/or fixed electronic devices [28]. It operates in unlicensed 2.4 GHz frequency band and has very low power consumption and short range (10 m). It is adequate for audio and simple file transfers. Bluetooth is nowadays increasingly being used to connect mobile phones and vehicles. This enables, for instance, to hands-free call from the vehicle, control a mobile phone using the vehicle's display, download travel information, access the Internet, etc.

ZigBee

ZigBee is a low-cost and low-power wireless PAN standard [29] which intends to satisfy the needs of sensors and control devices. ZigBee is built upon the IEEE 802.15.4 standard [30], which defines the Physical and MAC layers for low data rate and low cost personal area networks. These networks are characterized for being easy to install and simple/flexible, for providing reliable data transfer, short-range operation, being low cost, and providing a reasonable battery life. ZigBee specifies the higher layers of the protocol stack. Essentially, ZigBee works on two physical modes: 868-915 MHz and 2.4-2.4835 GHz, with possible data rates of 20–40 Kb/s and 250 Kb/s, respectively. ZigBee is commonly used in monitoring/controlling applications that have heavy requirements regarding latency and energy consumption (although not bandwidth demanding) - e.g. air conditioning, lighting control, etc.

Cellular Networks

The Universal Mobile Telecommunications System (UMTS), used mainly in Europe, is a Third Generation (3G) cellular network technology. UMTS is entirely packet-switched which permits a more efficient multiplexing of users streams, and the theoretical maximum throughput for the first UMTS release (release 99) is 384Kb/s. Later releases of the UMTS (releases 3 to 8) introduced new techniques (such as Time Division Synchronous Code Division Multiple Access (TD-SCDMA), High-Speed Downlink Packet Access (HSDPA) or Multiple Input Multiple Output (MIMO)) that ultimately allowed the achievement of greater peak data rates - for example, it achieved 42Mb/s in the downlink (using MIMO together with 64QAM modulation) and 11.5 Mb/s in the uplink (when using the 16QAM modulation). These mentioned releases are considered to be 3G transitional technologies, since they were the first steps towards a new type of cellular networks: 4G networks. The last step taken by 3GPP on transitional technologies was to develop Long-Term Evolution/Evolved Universal Terrestrial Radio Access (E-UTRA). LTE (first introduced in 3GPP Release 8) is the access part of the Evolved Packet System (EPS). LTE supported theoretical peak data rates of 300 Mb/s in downlink and 75 Mb/s in uplink direction. However, and even with some reviews on Release 9, LTE was not ready to fulfill the requirements to be considered as 4G, established by ITU-R [31]. LTE Advanced (E-UTRA) - the first effective 3GPP 4G technology - was finally introduced in Release 10 in March 2010. LTE-Advanced provides 1 Gb/s downlink and about 500 Mb/s uplink for fixed wireless, while mobile access is around 100 Mb/s on the downlink and 75 Mb/s on the uplink.

Worldwide Interoperability for Microwave Access and High Performance Radio Metropolitan Area Network

In parallel to the 3GPP work, the IEEE 802.16 standardization group (commonly known as WiMax - Worldwide Interoperability for Microwave Access) developed the IEEE 802.16-2001 initial specification and adopted the 10 to 66 GHz frequency band for fixed Broadband Wireless Access (BWA). The first standard went to a process of amendments (IEEE 802.16c-2002, IEEE 802.16a-2003, IEEE 802.16-2004) but support for mobility was only introduced when standard IEEE 802.16e-2005 (known as Mobile WiMax) was released. This standard provided enhancements to IEEE 802.16-2004 to support subscriber stations moving at vehicular speeds. It was able to provide, per sector, peak downlink data rates up to 63 Mb/s and uplink data rates of 28 Mb/s in a 10 MHz channel [32]. The technologies implemented by Mobile WiMAX result in lower equipment complexity and simpler mobility management due to the all-IP core network (from WiMax network architecture). HiperMAN (High Performance Radio Metropolitan Area Network) is a standard created by ETSI (European Telecommunications Standards Institute) to provide a wireless network communication in the 2–11 GHz bands in countries which follow the ETSI standard. HiperMAN [33] is the European alternative to WiMAX and Korean technology WiBro. It was were developed in cooperation with IEEE 802.16, so that the HiperMAN standards and a subset of the IEEE 802.16a-2003 standard can work together smoothly. IEEE 802.16m (also known as Mobile WiMAX Release 2 or WirelessMAN-Advanced) is an amendment to the IEEE 802.16-2009 standard and its main goal is to meet the requirements for IMT-Advanced next generation networks. IEEE 802.16m is designed to support frequencies in all licensed IMT bands below 6 GHz. The new standard provided enhancements in terms of coverage and spectral efficiency, capacity for data and VoIP, latency, QoS, power conservation, etc. This enabled the achievement significantly higher peak and average data rates than was possible before - allowing peak data rates that exceed 1 Gb/s.

Light Fidelity

Light Fidelity (Li-Fi) is a bidirectional, high speed and fully networked wireless communication technology that enables electronic devices like computers, laptops and smartphones to connect to the Internet via wireless. In simple terms, Li-Fi is similar to Wi-Fi, but it uses light waves from Light Emitting Diode (LED) light bulbs to transmit data, instead of radio signals. Li-Fi provides illumination and wireless data communications. The main difference between Li-Fi and Wi-Fi is bandwidth available - Wi-Fi uses radio frequencies which are very limited (devices like computers and smartphones are constantly competing for bandwidth) while Li-Fi uses the frequencies of light waves, which are much more plentiful. Some researchers [34] already demonstrated that it is possible to achieve 3 Gb/s on a single color LED. IEEE recognized the potential of this technology and introduced the IEEE 802.15.7-2011 [35] standard, which defines PHY and MAC layers for Visible Light Communication (VLC) supporting data rates up to 96 Mb/s by fast modulation of optical light sources. LED-based VLC systems can be deployed in vehicular environments using existing infrastructures such as LED-based traffic lights [36]. These infrastructures can be used to, for instance, disseminate road traffic information that helps to minimize accidents and ease the traffic flow.

Dedicated Short-Range Communications

Dedicated Short-Range Communications (DSRC) are radio communication channels specifically designed for automotive use and a corresponding set of protocols and standards. In the United States, the Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz frequency band to be used by ITS [37]. The first effort at standardizing DSRC was made by ASTM International with the release of the ASTM E2213-03 standard specification (which was based on IEEE 802.11a). In 2004, IEEE took over ASTM work and developed the IEEE 802.11p standard. IEEE 802.11p, also commonly known as WAVE, is an amendment to the traditional IEEE 802.11 standard to add wireless access in vehicular environments. In summary, it defines 802.11 improvements required to support ITS applications. This includes data exchange between high-speed vehicles and between the vehicles and the roadside infrastructures in DSRC. IEEE 1609-X is the set of higher layer standards that complement IEEE 802.11p to enable DSRC operations. Since WAVE standard is limited by the scope of IEEE 802.11 - related only to MAC and PHY - all additional knowledge and complexities are specified by the IEEE 1609-X set of standards. IEEE 802.11p uses 10 MHz channels and supports a very high data rate (6–27 Mb/s) with a maximum communication range of 1000 m. In

Europe, the ETSI allocated spectrum [38] in the 5.9 Gigahertz (GHz) band for DSRC applications. ITS-G5 is defined as the set of protocols and parameters specified in ETSI EN 202-663 [39].

Communication Access for Land Mobile

Communication Access for Land Mobile (CALM) is an architecture defined by ISO's Technical Committee 204 - Working Group 16 (TC204 WG16). CALM is designed to allow interoperability between ITS stations that abstract applications and services from the underlying communication layers. Its main goal is to establish an integrated technology that is able to provide a set of protocols for ITS communication using several different media [9]. The core concept of CALM is to enable vehicles to use any kind of communication media with seamless media handover. The set of CALM standards include specifications for: ITS station management; Communications security; Facilities, Station Networking and Transport layers protocols; Communication Interfaces and Services; Interfacing Technologies into ITS Stations; Distributed Implementations of ITS Stations; Interfacing ITS Stations to existing communication networks. CALM introduces specifications for mediums such as cellular networks, M5 or millimeter wave air interface.

4. Discussion

This section presents a summary and comparison of the technologies, discussing the appropriate and common use for each one.

Looking at wired networking technologies in the automotive domain, LIN and CAN are the strongest technologies and they co-exist well. Current solutions combine the use of LIN networks interconnected by a CAN backbone network, since it is an efficient solution and cheaper than an all CAN network. CAN is typically used for mainstream powertrain communications, LIN for lower-cost electronics and FlexRay for higher-bandwidth, safety critical applications. The main advantages of FlexRay over CAN and LIN are its flexibility and higher maximum data rate (10 Mb/s). Additionally, FlexRay can also be employed as a network backbone, working in conjunction with CAN and LIN networks. MOST is mostly used in networking for multimedia and infotainment systems, since its data rate (up to 150 Mb/s) makes it more suitable than other solutions for multimedia. However, and essentially due to problems related to limited bandwidth and a large number of networks and cabling that exist in vehicles, the tendency is to resort to new Ethernet solutions like the BroadR-Reach Ethernet standard, which are characterized for being fast, flexible and cheap solutions, while providing enough bandwidth for all the existent communications inside the car.

When it comes to wireless technologies, the most popular is IEEE 802.11p. DSRC or ITS-G5 are mainly used in electronic toll collection, but may also be used for applications which are very demanding like forward collision warning or approaching emergency vehicle warning. Being built specifically for vehicle environments, it can work for all kind of vehicle applications. However, its main drawback is range (only up to 1km). When DSRC communication is not possible due to range constrains, systems typically resort to cellular or WiMax/HiperMAN networks, since they work on a wider range and have acceptable latencies and data rates, being useful for soft-safety applications or infotainment. 3G networks offer low latencies that can meet the requirements of safety appli-

cations in vehicle environments however, they lack support of V2V local broadcasts that are crucial when using hard safety applications. Additionally, sharing bandwidth with voice communications causes unpredictable delays and may overload the system. Also, due to the long call setup latencies, an excessive delay can prevent its use in safety applications. 4G networks offer significantly lower communication delay, higher capacity and enhanced broadcasting capabilities when compared to 3G. Therefore, 4G can support time-critical vehicle applications, including I2V local broadcast. Bluetooth may be used in some particular V2I or V2V communications (e.g. vehicle is stopped or moving very slowly). However, its limited communication range and high latency prevents it from supporting vehicle safety communications. Thus, it is not very adequate for something more than enhancing the driving experience. Similarly to Bluetooth, ZigBee is aimed for specific purposes - it can be found in many of automotive sensor networks for monitoring and control purposes (e.g. air conditioning, lighting control). Li-Fi systems can be deployed in vehicular environments using existing LED-based traffic lights infrastructures [48], which can be used to, for instance, disseminate road traffic information that helps to minimize accidents and ease the traffic flow (typical I2V environment). Li-Fi may also be effective in V2V situations by using LED headlights/brake lights. For instance, a vehicle in front of a traffic light is able to receive information and relay it to the vehicle behind by using the brake lights. CALM methods of transmission can be used in several communication media (e.g. 3G, DSRC, WiMax, etc.) and thus can be applied in any type of applications ranging from Internet access to collision avoidance and in any communication mode (I2V, V2I and V2V). CALM allows dynamic selection of communication profiles dependent on needs of applications and capabilities of the access technologies.
Table 1 illustrates the mapping between applications and the recommended carriers. The table nomenclature assumed is similar to the one used in [9], emphasizing the technologies that were described in this work. ITS applications categories and their requirements can be found on the ETSI TR 102 638 standard [40], which describes a *Basic Set of Applications* focused on V2V, V2I and I2V communications.

Table 1. Recommended Technologies for ITS Applications

Applications	ITS Application Category	Recommended Technologies
Safety	Collision Avoidance	DSRC
	Road Sign Notifications	DSRC, Li-Fi
	Incident Management	DSRC, 3G/4G
Efficiency	Traffic Management	DSRC, 3G/4G
	Road Monitoring	DSRC, 3G/4G, Li-Fi, ZigBee
Comfort	Entertainment	DSRC, 3G/4G, Li-Fi, ZigBee, Bluetooth
	Contextual Information	DSRC, 3G/4G, Li-Fi

5. Conclusion

Vehicular communication technologies are the enabling factor that gives support to a wide range of use cases and applications in vehicle environments, ranging from social networking to critical safety applications. This paper presented a survey of the most commonly discussed automotive networking technologies (both wired and wireless), identifying their main characteristics and to which vehicular context may applied. Wired communication technologies such as CAN, LIN and FlexRay tend to coexist well in vehicle environments, although the tendency is for manufacturers to start implementing Ethernet solutions, due to their benefits in terms of complexity, cost or even cabling weight. Wireless technologies such as ZigBee, Bluetooth or LiFi are considered for very specific problems such as connecting the vehicle to the drivers smartphone, or taking advantage of the existing traffic lights infrastructures to disseminate traffic information. IEEE 802.11p is the most interesting solution for wireless vehicle communications, with exception for applications that require long range communication (more than 1 km) or have high bandwidth demands (typically infotainment applications). In this case, vehicles tend to resort to solutions such as cellular networks or WiMax to overcome this limitations.

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