A Survey of In-vehicle Communications: Requirements, Solutions and Opportunities in IoT

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***Abstract*—As the automobile industry evolves, a number of in-vehicle communication protocols are developed for different in-vehicle applications. With the emerging new applications towards Internet of Things (IoT), a more integral solution is needed to enable the pervasiveness of intra- and inter-vehicle communications. In this survey, we first introduce different classifications of automobile applications with focus on their bandwidth and latency. Then we survey different in-vehicle communication bus protocols including both legacy protocols and emerging Ethernet. In addition, we highlight our contribution in the field to employ power line as the in-vehicle communication medium. We believe power line communication will play an important part in future automobile which can potentially reduce the amount of wiring, simplify design and reduce cost. Based on these technologies, we also introduce some promising applications in future automobile enabled by the development of in-vehicle network. Finally, We will share our view on how the in-vehicle network can be merged into the future IoT.**

I. INTRODUCTION

The in-vehicle network involves communications among different electronic control units (ECUs), sensors and actuators. According to the Society of Automotive Engineers (SAE), the number of ECUs in an automobile ranges from 30 for simple cars to approximately 100 for luxury cars [1]. The electronics accounts for 15 percent of total vehicle cost in 2005 climber from 5 percent in the late 1970s. Today, vehicles are increasingly behaving as an intelligent computing system.

At early stage of automobile design, in-vehicle networks are realized through point-to-point wiring between electronic components, resulting bulky, expensive, complicated harnesses [2]. With increasing scale and complexity of in-vehicle network, the in-vehicle network grows into a state where volume, weight and reliability becomes a real problem.

As a result, a more integral solution is called for and several automobile communication bus protocols are developed. By connecting a number of the electronic components to the same in-vehicle communication bus, the communications medium can be shared and wiring can thus be saved. Meanwhile, the in-vehicle architecture can be more hierarchical and structural, which also simplifies the automobile designing procedure.

This paper is organized as follows. In section II, we elaborate different classifications of automobile applications. In section III, we summarize different in-vehicle communication bus protocols. In section IV, we introduce several new emerging applications in the automobile and how the automobile can be emerged into the IoT. Conclusions and outlooks are drawn in section V.

II. CLASSIFICATIONS OF AUTOMOBILE APPLICATIONS

Each in-vehicle communication bus protocol is developed to support certain kinds of automobile applications. The SAE takes class A, B, C, D classification with increasing order of requirements in bandwidth, latency and reliability [2]:

A. Class A

Class A demands the lowest data rate, a rate that peaks as high as 10Kb/s. Class A must support event-driven message transmission and its usage is for low-end, non-emission diagnostic, general purpose communication. The implementation of Class A has significantly reduced the bulk of automobile wiring harnesses. The cost of Class A is generally about ”x” per added node. A rough estimate of 0.50 to 1 may be used for the value of ”x” . This cost includes any silicon involved, software, connector pins, service, etc.

Class A devices typically support convenience operations. Typical applications include controlling lights, windshield wiper, doors and seats. The latency requirement for Class A applications is varied from 50ms to 150ms.

B. Class B

Class B supports data rates approximately between 10 Kb/s and 125 Kb/s. Class B must support event-driven and some periodic message transmission with sleep/wakeup function. It typically supports the vast majority of non-diagnostic, non-critical communication. The utilization of Class B can eliminate redundant sensors and other system elements by providing a means to transfer data (e.g. parametric data values) between nodes. The cost of Class B is around 2x per node.

The shared information on a Class B network is not critical to the operation of any system related. The delay of a specific piece of information will not cause a critical failure in any of the systems. Therefore, the response window in a Class B network is not nearly as narrow as in a Class C network.

C. Class C

Class C can support data rate ranging from 125 Kb/s to 1 Mb/s. Because of the comparatively high data rate supported, Class C facilitates distributed control via high data rate signals typically associated with critical and real-time control systems (perhaps in the few milliseconds range), such as control of engine and suspension, etc. Unshielded twisted pair is the medium of choice for real-time control applications. The cost of class C is about 3x to 4x per node. However, the upper end to Class C utilization relies on expensive media, like fiber optics, that can push node costs much higher than estimated.

D. Class D

Class D supports data rates over 1 Mb/s. With such level of performance, Class D is devoted to applications demanding very high bandwidth and strict latency constraint. Due to the high bandwidth supported by class D, it is well suited to the applications of high resolution video entertainment system and Advanced Driving Assistance System (ADAS). With ADAS, an additional bandwidth approximately between 10 Mb/s to 30 Mb/s is required. Class D can also be implemented to meet strict latency constraint within 2ms. In this aspect, Class D also suits the safety critical applications. Some applications of ADAS could be safety critical in which case both high bandwidth and strict latency are required. X-by-wire is another example where strict latency constraint should be fulfilled.

III. In-Vehicle Communication Bus Protocols

In this section, we introduce the main standards used in automobile industry, in particular the networks and their protocols. Due to different cost, reliability, bandwidth, latency requirements imposed by different classifications of automobile applications, specific communication protocols and networks have been developed.

A. Local Interconnect Network (LIN)

LIN is a low cost serial bus network used for distributed body control electronic systems in vehicle. The standard is described at [3]. The LIN consortium includes VW/Audi, Daimler-Chrysler and Motorola.

The silicon implementation of LIN is cheap and LIN can be implemented using just a single wire. LIN is a single master/multiple slave non-arbitration architecture. The master poll at most 15 slaves periodically. In the hierarchical network architecture, LIN is commonly used as a sub bus for CAN and FlexRay. LIN is time triggered and the maximum message latency is therefore guaranteed. The communication speed of LIN can reach as high as 20Kbit/s. Thus while LIN is considered to be most appropriate for SAE class A applications, it is actually at the lower end of class B. The data length of LIN can be 1/2/4/8 bytes.

B. Controller Area Network (CAN)

Currently, CAN is without any doubt the mostly used in-vehicle network. CAN is a network protocol developed by Robert Bosch GmbH for vehicle systems [4]. However, CAN is actually coming into use for linking distributed controllers, sensors etc in other fields. Low-speed CAN supports Class B applications used for body domain. High-speed CAN supports more real-time critical functions in powertrain and chassis domain.

CAN is a priority-based bus implemented by using two wires. The Medium Access Control (MAC) protocol of CAN uses carrier sense multiple access with collision detection (CSMA/CD). Up to 8 bytes of data can be carried by one CAN frame and a cyclic redundancy check (CRC) of 16 bits is used for transmission error detection. CAN facilitates bit by bit non-destructive arbitration over the identifier which serves also as priority.

Low-speed CAN supports data rate ranging from 10 kb/s to 125 kb/s while high-speed CAN reaches 125 kb/s to 1 Mb/s suitable for real-time control applications. However, It is worth noting that CAN is not suited for safety-critical applications, such as some x-by-wire systems, because the main drawback is the lacking in self diagnosis. CAN is also not suitable for transmission of messages of large data sizes.

C. FlexRay

FlexRay is a protocol with net data rate 5 Mb/s which combines time triggered (primary) and event triggered messaging. It is being developed by BMW and DaimlerChrysler with Philips and Motorola [5]. FlexRay is a protocol in the bus architecture for safety-critical embedded systems and advanced control functions. FlexRay should be classified into Class D networks devoted to x-by-wire applications that need predictability, fault tolerance and deterministic real-time behaviour.

The FlexRay network supports redundancy and is very flexible with regard to topology. It can be configured as a bus, a star or multi-stars.

At the MAC level, FlexRay defines a communication cycle as the concatenation of a time triggered static window and an event triggered dynamic window. The communication cycles are executed periodically. Time-triggered operation provides efficiency, determinism and partitioning, but at the price of flexibility, whereas an event-triggered system responds to stimuli that are outside its control.

D. Media Oriented System Transport (MOST)

MOST is a multimedia fibre optic network developed in 1998 by MOST coorperation [6]. It is the de-facto standard for multimedia and infotainment networking in the automobile industry. The basic application modules supported by MOST are audio and video transfer, based on which end-user applications like radios, GPS navigation, video entertainment systems can be built.

The MOST protocol defines separate data channels and control channels. The control channels are used to set up the data channels for each link. Once the connection is established, data can flow continuously for delivering audio or video stream. MOST provides point-to-point audio and video data transfer with a data rate of 24.8 Mb/s. Thus MOST is classified into Class D networks devoted to multimedia data.

E. Ethernet

IEEE 802.3 Ethernet [7] is a commonly utilized CSMA/CD communication bus protocol due to its low cost, fast speed and high flexibility. Not surprisingly, Ethernet is the technology of choice for much of the Internet and the most popular technology for local area network (LAN) in computer networking. The motivation to implement Ethernet in in-vehicle network is the ever increasing bandwidth demanded by automobile applications, especially video-based ADAS.

The uncompressed video stream transmission will not be uncommon in video-based ADAS of future automobile. A single 1280×960 pixel resolution camera stream at 30 frames/s requires 884.74 Mb/s bandwidth which is not supported by any existing automobile communication bus protocol. As we can see, the gigabit Ethernet is right in the place to suit the emerging bandwidth requirement. With Audio Video Bridging (AVB) implemented over switched Ethernet, the latency can be guaranteed within 2 ms in 7 hops. Due to Ethernet's high bandwidth, low latency, high reliability and high flexibility, it is becoming more and more clear that Ethernet will be the backbone for future in-vehicle network [8].

Of many choices for Ethernet implementation, unshielded twisted single-pair (UTP) is promoted by OPENSIG with its members BMW, Daimler, Nissan, and Renault. UTP makes Ethernet small, flexible, lightweight and cheap to manufacture. It is shown that UTP implementation realizes as high as 100 Mb/s full duplex data rate, which is enough for compressed video transmission. To support uncompressed video stream transmission, the IEEE Reduced Twisted Pair Gigabit Ethernet (RTPGE) Study Group is dedicated to modify the current IEEE 802.3 protocol to realize gigabit Ethernet with only three pairs of twisted copper cable.

F. Power Line Communication (PLC)

PLC technology grants to use existing power line to transfer both power and data. Fabricated by Yamar Electronics Ltd., Semiconductors for direct current (DC) and alternating current (AC) power line communications have been applied in various applications, including automotive, train, aerospace, white-goods and lighting. By implementing PLC over DC power line in automobile [9], duplicate wiring of power line and communication bus can be avoided. PLC is extremely beneficial where cabling space is strictly restricted, which is not an uncommon scenario, since in automobile much of the physical space is taken up by the passenger cabin. Using PLC also helps to reduce amount of wiring, which not only saves cost in automobile design and manufacture, but also reduces the weight of automobile. It is worth noting that total wiring in automobile weighs more than 45 kilograms. With PLC implemented, it is potential we reduce the weight of the automobile by as much as 30 kg. As a result, fuel consumption is reduced and green house gas emission is cut down.

We believe in the next generation automobile, there will be a more integral and more homogeneous in-vehicle network. Ethernet will provide the backbone and as a subnet connected to the backbone, PLC will be an attractive supplement where Ethernet wire can not reach because of its advantages described above. In the development of in-vehicle network within next few years, more and more legacy network will be replaced by the PLC network.

Our research work is focused on this area and we are particularly interested in HomePlug Green PHY (HomePlug GP) [10] due to its universal applicability, compact size, low cost, reduced overhead and high reliability.

Developed by HomePlug Alliance, HomePlug GP is a broadband PLC protocol using frequency band from 1.8 MHz to 30 MHz for data transmission. The broad band composed of a number of orthogonal frequency-division multiplexing (OFDM) channels can be utilized to support high data rate and to provide high robustness. The PLC channel in automobile is a noisy channel with fast, unpredicatable varying [11], which poses a challenge in the guarantee of data transmission reliability. The physical layer exploits several forward error correction (FEC) techniques to combat the noisy channel, such as turbo convolutional code encoding, diversity copying, scrambling, channel interleaving. HomePlug GP supports three ROBO modes, namely MINI-ROBO, STD-ROBO, HS-ROBO with data rates 3.8 Mb/s, 4.8 Mb/s, 9.8 Mb/s respectively.

The MAC protocol of HomePlug GP is carrier sense multiple access with collision avoidance (CSMA/CA). After the channel is sensed idle for a contention interframe space (CIFS), a MAC frame begins with priority resolution. HomePlug GP implements strict priority selection algorithm with four priority levels. Higher priority MAC frame always goes prior to transmission of lower priority MAC frame.

Higher priority MAC frame will start random backoff while nodes with lower priority level will keep continuously listening to the channel until the channel is sensed idle for CIFS again. When the backoff counter reaches zero, the node will get access to the communication channel and start to transmit the message, which consists of the frame control message followed by MAC data payload. The frame control counts 128 bit in total while the data payload can be a single 136 byte physical block or multiple times (possibly only one)

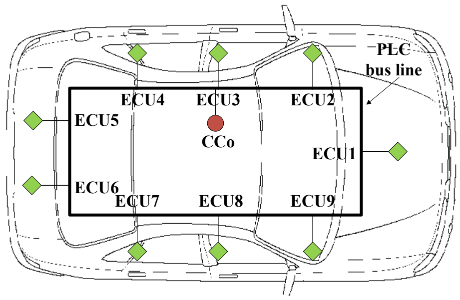

Fig. 1. Simulation Topology

of a 520 byte physical block. When two nodes both transmit, a collision will happen. Upon collision or the case when the counts of message delay reach a certain limit, the network node will increase its backoff window exponentially to avoid collision.

Upon the destination correctly(incorrectly) receives the frame, it will send out ACK(NACK) after response interframe space (RIFS). Note that if there is a collision or there is an error in the frame control, the destination is not able to send ACK or NACK in which case the source decides a collision after the timer expires.

HomePlug GP has its success in home area network (HAN) applications. However, some modifications are necessary to suit the needs of automobile applications. There are ongoing work refining the PLC protocol both on physical layer and MAC layer. Taherinejad *et al.* designs an adaptive impedance matching circuit to combat the fast varying PLC channel characteristic [12]. Antonioli *et al.* designs a real-time MAC protocol for in-vehicle PLC based on HomePlug with reduced overhead, reduced collision rate and fast collision resolution [13]. Sheng *et al.* proposes a multi-channel MAC protocol for vehicular power line communication systems which resolves collision in time-frequency domain and aims to reduce the collision overhead [14].

In our recent work, we enhance packet queuing behaviour in in-vehicle PLC network utilizing virtual collision (VC) and IEEE 802.1Qav credit based shaping (CBS) [15]. We set up the simulation (topology shown in Fig. 1) using OMNeT++ to verify the effectiveness of our proposed method. Fig. 2 shows the latency performance of a same in-vehicle flow using different bus protocols. Note the x-axis corresponds to the maximum latency value sampled from ten independent network nodes rather than different simulations carried out with different number of nodes. Moreover the connection of data in Fig. 2 only shows the data variation rather than showing any trend. The HPGP corresponding to the original HomePlug GP protocol has latency performance below the satisfaction level, i.e. 5ms. With VC and AVB CBS implemented, the delay performance can be well managed within the deadline and also closed to the ideal centralized (IC) optimal benchmark.

We believe in the near future PLC will be a promising

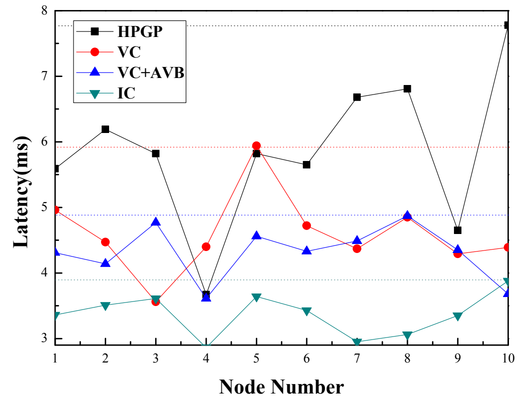

Fig. 2. Latency Performance of the Proposed PLC Protocol based on HPGP

alternative in the next generation in-vehicle network.

IV. Automobile Application and its Opportunity in IoT

Along with the development of IoT [16], the area of automobile applications is now rapidly growing, offering great potential for enhancements in convenience, safety and efficiency. We will also share our view on how the in-vehicle network can be merged into the future IoT.

A. ADAS

The in-vehicle systems that help drivers in the driving process are called ADAS. The ADAS provides extra useful information to the driver and enables active safety function. Applications of ADAS are usually designed with an interactive interface to improve driving performance and further ensure road safety, such as lane departure detection, driver monitoring. Thanks to the continuous development of in-vehicle network, the gigabit Ethernet provides ample bandwidth and AVB operated over Ethernet provides latency guarantee seven hops within two milliseconds. As bandwidth and latency requirements required by ADAS applications can be fulfilled, these applications are now booming, making vehicles smarter and safer.

1) Lane Departure Detection: The lane departure detection system receives data from lane detection module to conjecture whether the vehicle is about to cross the lane boundary within the next few tenths of a second. In that case, if the driver does not signal his intent to switch lanes, a warning is issued.

There are primarily two types of lane departure detection systems. The first type is typically referred to as Lane Departure Warning (LDW) system [17]. LDW system monitors the lane markings on the roadway and triggers an alarm whenever a vehicle starts to deviate from its lane.

The other type is more proactive and is often referred to as a Lane-Keeping System (LKS) [18]. LKS also monitors lane markings but with additional capability to take corrective actions. If the driver doesn't respond to an initiated warning, LKS will take proactively measures to keep the vehicle from drifting.

Lane departure detection systems are based on: video sensors in the visual domain (mounted behind the windshield), laser sensors (mounted on the front of the vehicle) and infrared sensors (mounted either behind the windshield or under the vehicle). Original equipment manufacturer (OEM) testing has proven that LDW performs well in diverse light and weather conditions on diverse types of roads.

2) Driver Monitoring System: One of the main reasons of traffic accidents is driver's fatigue and negative mood, which decrease drivers' vigilance level and result in 600 people's death on road each day [19]. Therefore, it is of great importance to monitor the mood and fatigue level of drivers in real time and take actions according to the vigilance level estimated.

Wenyan Hu *et al.* [20] built a Mood-Fatigue Analyzer (MFA) which collects the real-time sensing data from driver behaviours (such as the expression and eye-lid), cars situation (such as the engine rotation speed), and outside environment (such as the temperature and humidity). By analyzing the data collected, MFA outputs a multidimensional indicator showing the current states of driver, vehicle and outside environment, based on which the mood and fatigue degree of the driver is decided. Finally, it takes measures to improve the driver's emotion and fatigue status such as playing suitable music or giving other positive stimuli. MFA can also share the drivers' driving experience with their friends via social networks, which helps to relieve the driver's negative mood as well.

Taking advantage of the development of IoT, MFA, as a typical example of ADAS, takes appropriate measures based on driver's mood-fatigue situation monitored, by which means driving performance is enhanced and road safety level is improved.

B. Connected Vehicles

The term connected vehicles refers to applications, services, and technologies that connect a vehicle to its surroundings through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications [21]. According to Gartner, Inc., there will be one-quarter billion connected vehicles on the road by 2020.

Connected vehicle applications can generally be categorized into three classifications, road safety applications, road efficiency applications and value-added service. Road safety applications typically impose stringent latency requirement and high reliability demand. Examples of road safety applications include warnings of lane changes and warnings of sudden break.

Road efficiency applications aim at enhancing road traffic flow, improving road traffic conditions and reducing traffic congestion. With road efficiency applications, emission of green house gas and pollution gas will potentially be reduced. Examples of road efficiency applications include green-light optimal speed advisory and enhanced route guidance.

Some value-added services providing convenience topassengers will also be supported by connected vehicle applications, e.g. informing of grocery stores and petrol stations nearby.

With the enhanced road safety, improved road efficiency and additional passenger convenience provided by connected vehicle applications, it is worth noting that the in-vehicle network is an indispensable component in the connected vehicles. Connected to other vehicles and infrastructures, vehicles share the information acting both as information collector, sender and receiver. Sensors in vehicles collect information on road and send the data through in-vehicle network to ECUs for data processing. The ECUs decide there is a potential hazard and send command through in-vehicle network to the transmitter for warning dissemination. Upon other vehicles' receiving of the warning, the in-vehicle network is also intensively involved before the actuators in those vehicles take appropriate measures to avoid the potential road hazard condition.

C. Smart Charging

Electric vehicles (EVs) are now developing rapidly due to their environmental friendliness and high energy efficiency. Operated with clean energy, EVs are expected to have a noteworthy contribution to the urban air quality. Meanwhile, according to the official U.S. government source for fuel economy information, EVs are capable of converting 59%-62% of the electrical energy drawn from the grid to propulsion while an internal combustion vehicle (ICV) can only convert 17%-21% energy stored in the gasoline to power at wheel.

Cheaper batteries with more capacity are under development and charging stations for EVs are under construction. It is foreseen in the near future that more and more ICVs on road will be replaced by EVs. However, the growth of penetration of EVs also poses great challenges to the power grid because the plugging of EVs to the charge station will induce a large amount of grid electricity, which will disrupt the power grid to a great extent if not treated appropriately [22]. Thus it is important to charge the EVs in a smart way in order to make the power grid operate stably and smoothly.

Smart charging of an EV enables the charging cycle to be altered by external events, which allows for adaptive charging habits. Based on a hierarchical smart control structure, smart charging actively controls the charging cycle of EVs to balance the load and avoid the congestion. As a result, the voltage profile of the grid is improved which alleviates the above mentioned challenge posed to the power grid. Furthermore, based on future prediction, Lopes *et al.* [23] proposes a smart charging strategy to better utilize the resources based on the prediction of renewable energy surplus.

Lots of research has been done on smart charging to optimize the mobility and energy use [24]. Smart charging provides the EV with the ability to integrate into the power system in both a grid- and a user-friendly way. Smart charging must facilitate the stability and reliability of supply while meeting the mobility requirements of the user. To achieve such goals in a safe, reliable, sustainable and efficient manner, information needs to be exchanged between different EVs, charging infrastructure and grid control. The development of in-vehicle network provides a promising candidate for the solution to the communication required by the smart charging application. By plugging the PLC enabled EV to the charging station, the status of the EV, e.g. the identification information of the vehicle crucial for charging initialization and the state of charge of battery of the vehicle important for charging schedule optimization, can be readily acquired through the in-vehicle power line connected to the charging infrastructure.

D. Future Outlook of Automobile in IoT

In the future, the IoT technology will certainly grant us more than what we have expected. In IoT, each object can take part in the network and everything is connected to each other. Information is shared and utilized will.

In future IoT, a vehicle is able to drive itself automatically to pick up the passengers. Upon arriving, the vehicle will seat the passengers comfortably by automatically adjusting the angle and position of the seat according to each passenger's profile and preference stored in online databases. The intelligent sensor detects passenger's mood during the driving and the in-vehicle entertainment system plays appropriate music accordingly. When the vehicle sends the passenger to the destination, it will find a place to park itself automatically and wait for future calling.

The vehicle is able to send the passengers to the destination timely, safely and automatically. The vehicle is aware of other vehicles, pedestrians, obstacles nearby and can automatically avoid them. With information shared on the road, the vehicle can make some pre-judgements on road conditions within the next few seconds, in avoid of sudden brake and degraded passenger experience. In future IoT, one vehicle goes after another with the optimized speed without halt and congestion.

V. CONCLUSION

This paper has introduced different classes of automobile applications, in-vehicle communication bus protocols. We believe that Ethernet will be the backbone network for future automobile and the PLC is bound to play an important role in the future in-vehicle network. Then some promising automobile applications have been introduced. Finally, we share our view on the future automobile in IoT.

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