A Survey of Automotive Networking Applications and Protocols

In this survey, we summarize automotive applications and provide an outline of the main standards used in automotive industry, in particular the networks and their protocols. Moreover, we analyze and provide some insights on how the standard solutions can cope with application characteristics.

1 Automotive applications

The Society of Automotive Engineers (SAE) has classified the automotive applications into classes A, B and C with increasing order of criticality on real-time and dependability constraints [1], [2].

- Class A, low speed (less than 10Kb/s) for convenience features such as body and comfort.
- Class B, medium speed (between 10 and 125Kb/s) for general information transfer, such as emission data, instrumentation.
- Class C, high speed (greater than 125Kb/s) for real-time control such as traction control, brake by wire, etc.

1.1 Class A

Class A is the first SAE classification and maintains the lowest data rate, a rate that peaks as high as 10Kb/s and must support event-driven message transmission. Usage is for low-end, non-emission diagnostic, general purpose communication. The implementation of Class A has significantly reduced the bulk of automotive wiring harnesses. Cost is generally about "x" adder per node. According to the latest figure in 2010, a very rough estimate of $0.50 to $1 may be used for the value of "x" [3]. This cost includes any silicon involved (i.e. microprocessor module or transceiver, etc.), software, connector pin(s), service, etc.

Class A devices typically support convenience operations like actuators and "smart" sensors. Figure 1 provides a Class A application zone. Typical applications involving these networks include controlling lights, windshield wiper, doors (e.g., door locks, opening/closing windows) or seats (e.g., seat position motors, occupancy control). The latency requirement for Class A applications is varied from 50ms to 150ms [1]. It is noted that a full list of Class A application is by no means complete, and will vary from application to application.

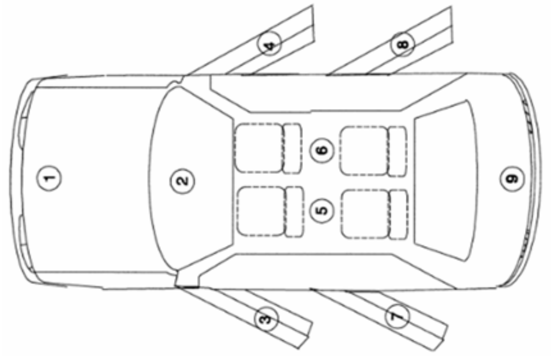

Figure 1 Class A application zone [1]

1.2 Class B

Class B supports data rates between 10 Kb/s and approximately 125 Kb/s and typically supports the vast majority of non-diagnostic, non-critical communications. 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 and it must support event-driven and some periodic message transmission plus sleep/wakeup. Cost is around 2x per node.

The shared information on a Class B network is not critical to the operation of all of the systems to which it is connected. The delay of a specific piece of information will not cause a critical failure in any of the systems. Therefore, the response window in the Class B network is not nearly as narrow as in the Class C. In fact, the response time may be variable, depending on the application. Another characteristic of Class B network is its interconnection of dissimilar systems. Figure 2 illustrates a Class B application.

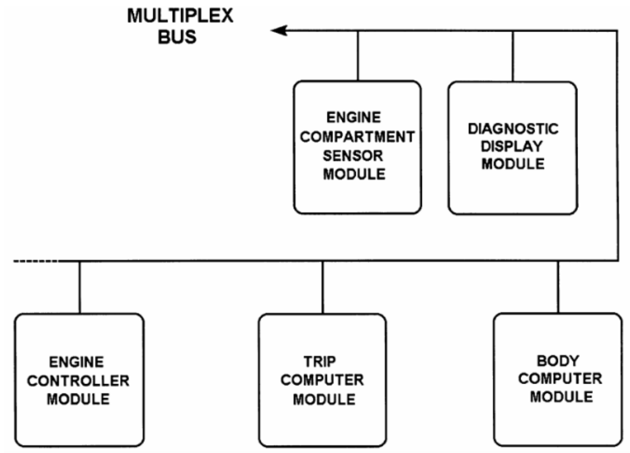

Figure 2 Class B multiplex application [1]

1.3 Class C

Class C can support data rate between 125 Kb/s and 1 Mb/s. Because of this level of performance, 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 instead of shielded twisted pair or fiber optics. Cost 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. Higher performance communication classifications from 1Mb/s to 10Mb/s are expected in the future. Classifications like Class D devoted to multimedia data (e.g., media-oriented system transport) can be expected to push forward the bandwidth and performance needs. Figure 3 illustrate typical Class C applications.

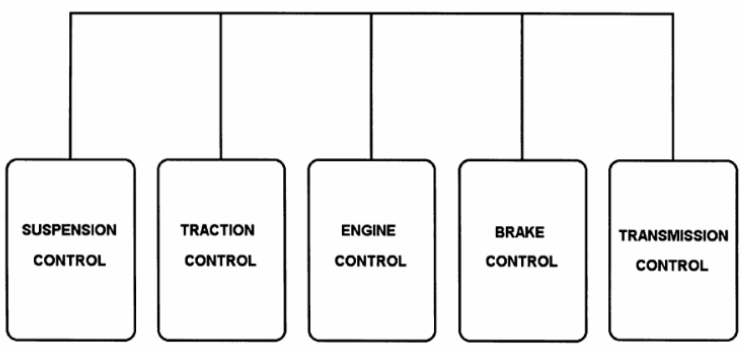

Figure 3 Class C applications [1]

A hierarchical relationship exists between the classes of networks. By definition, Class C is a superset of Class B. Also, Class B is a superset of Class A. It should be noted that this is a functional relationship only. Therefore, it is important to distinguish between the function and the application of the multiplex network. Table 1 summarizes and compares characteristics of three application domains.

Table 1 Comparisons of fucntional classes

	Class A	Class B	Class C
Purpose	Sensor/Actuator control	Information sharing	Real-Time control
Information	Real time	Occasional	Real time
Latency Response Time	Wide window (<150ms)	Varying window	Narrow window
Priority level	Low (for non real-time)	Low (for non real-time)	High (real-time)
Information lost or corrupted	Nuisance	Nuisance or failure	Failure
Cost per unit	<1$	<2$	<4$
Application	Body domain, i.e., comfort	Multiplex bus can cover	Powertrain, i.e., control of

coverage	functions, dash board, wipers, lights, doors, windows, seats, mirrors, climate control, etc.	body domain and interactions among several function domains.	engine; Chassis, i.e., control of suspension, steering & baking. Telematics, multimedia and human-machine interface (HMI)

It is not a straightforward manner to compare priority levels among functional classes, since each application domain may be controlled by an isolated sub-system using one of BUS protocols. The allocation of application priority is up to a system designer, but industry groups mutually agree on the significance of certain application domains. For example, the Powertrain Control bus is the high priority information carrier, and the Body Control bus is the low priority information carrier [4].

2 Automotive networking protocols

In this section, we introduce the main standards used in automotive industry, in particular the networks and their protocols. Due to the stringent cost, real-time and reliability constraints, specific communication protocols and networks have been developed to fulfil the needs of the Electronic Control Unit (ECU) multiplexing. SAE has defined three distinct protocol classes named class A, B and C. Class A protocol is defined for interconnecting actuators and sensors with a low bit rate (about 10Kbps). An example is LIN. Class B protocol supports a data rate as high as 125Kbps and is designed for supporting non real-time control and inters ECU communication. Low speed CAN is an example of SAE class B protocol. Class C protocol is designed for supporting real-time and critical applications. Networks like high speed CAN belong to the class C, which support data rates as high as 1Mbps. There are even more advanced protocols supporting high speed communication, such as FlexRay and MOST.

2.1 Local Interconnect Network (LIN)

LIN is an acronym for Local Interconnect Network and is a low cost serial bus network used for distributed body control electronic systems in vehicle. The standard is described at [5]. The LIN consortium includes VW/Audi, Daimler-Chrysler and Motorola. Its development was driven by academic institutions.

It is a single master/multiple slave architecture. One node, termed the master, possesses an accurate clock and drives the communication by polling the other nodes—the slaves—periodically, so no need for arbitration. A master can handle at most 15 slaves (there are 16 identifiers by class of data length). As it is time triggered, message latency is guaranteed. Silicon implementation is cheap, based on common UART/SCI interface hardware and SCI stands for serial communications interface.

The LIN can be implemented using just a single wire and it is commonly used as a sub bus for CAN and FlexRay by building a hierarchical multiplex system. Speed is 20Kbit/s so while it is considered to be most appropriate for SAE class A applications, the speed is actually at the lower end of class B. The data length can be 1/2/4/8 bytes.

Typical applications involving these networks include controlling doors (e.g., door locks, opening/closing windows) or controlling seats (e.g., seat position motors, occupancy control).

2.2 Controller Area Network (CAN)

Controller Area Network (CAN) is without any doubt the mostly used in-vehicle network. It is a network protocol developed by Robert Bosch GmbH for vehicle systems, but which is coming into use for linking distributed controllers, sensors etc in other fields. The integrated mechatronic subsystems based on low-cost networks are usually interconnected through a CAN backbone. The protocol has been adopted as a standard by the ISO, reference ISO11898 [6].

CAN is a priority-based bus which allows to provide a bounded communication delay for each message priority. The MAC (Medium Access Control) protocol of CAN uses CSMA/CD with bit by bit non-destructive arbitration over the ID field (Identifier). The identifier is coded using 11 bits (CAN 2.0A) or 29 bits (CAN 2.0B) and it also serves as priority. CAN uses a NRZ bit encoding scheme for making feasible the bit by bit arbitration with a logical AND operation. Higher priority messages always gain access to the medium during arbitration. Therefore, the transmission delay for higher priority messages can be guaranteed. However the use of bit-wise arbitration scheme intrinsically limits the bit rate of CAN as the bit time must be long enough to cover the propagation delay on the whole network. Up to 8 bytes of data can be carried by one CAN frame and a CRC of 16 bits is used for transmission error detection. It supports speeds of up to 1Mb/s, suitable for real time control applications. CAN needs to be implemented using two wires and the event triggered nature is very efficient in terms of bandwidth usage.

Depends on the system requirements, CAN can support two classes of applications:

- Class B networks, between 10kb/s and 125 kb/s used for body domain (low-speed CAN)
- Class C networks, between 125 kb/s–1 Mb/s (high-speed CAN used for the powertrain and the chassis domains) for more real-time critical functions. If the distance is less than 40 m, the rate can be up to 1 Mbps.

CAN is not suited for safety-critical applications, such as some future x-by-wire systems, because the main drawback is that a node has to diagnose itself. CAN is also not suitable for transmission of messages of large data sizes, although it does support fragmentation of data that is more than 8 bytes.

2.3 FlexRay

FlexRay is a protocol that combines time triggered (primary) and event triggered messaging. It is being developed by BMW and DaimlerChrysler with Philips and Motorola, and its purpose is to provide for X-by-Wire applications with deterministic real-time and reliability communication. It is capable of a net data rate of 5Mbps (10 Mbps gross). It is a protocol in Bus architectures for safety-critical embedded systems and advanced control functions.

At the MAC level, FlexRay defines a communication cycle as the concatenation of a time triggered (or static) window and an event triggered (or dynamic) window. 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. To each communication window, whose size is set at design time, a different protocol applies. The time triggered window uses a TDMA protocol. In the event triggered part of the communication cycle, the protocol is FTDMA (Flexible Time Division Multiple Access): the time is divided into so called mini-slots, each station possesses a given number of mini-slots (not necessarily consecutive) and it can start the transmission of a frame inside each of its own mini-slot. A mini-slot remains idle if the station has nothing to transmit. The communication cycles are executed periodically.

The highest priorities in FlexRay usually have slots allocated in the static (time triggered) part, and lower priority sources in the dynamic (event triggered) part, so a source has a slot in one or the other. This presumably reduces jitter for messages allocated slots in the static portion (as compared to Byteight) as their timing is constant, unlike in Byteight, where vacant slots are shortened. FlexRay differs from SAFEbus and TTA in that the full schedule for the system is not installed in each node during construction. Instead, each node is initialized only with its own schedule, and learns the full configuration of the system by observing message traffic during startup.

The FlexRay network is very flexible with regard to topology and transmission support redundancy. It can be configured as a bus, a star or multi-stars and it is not mandatory that each station possesses replicated channels even though it should be the case for X-by-Wire applications. FlexyRay should be classified into Class D networks (speed over 1 Mb/s) which are x-by-wire applications that need predictability and fault tolerance.

2.4 Media-oriented system transport (MOST)

MOST (Media Oriented System Transport) [7] is a multimedia fibre optic network developed in 1998 by MOST coorperation (a kind of consortium composed of carmakers, set makers, system architects and key component suppliers). The basic application blocks supported by MOST are audio and video transfer, based on which end-user applications like radios, GPS navigation, video displays and amplifiers and entertainment systems can be built.

The MOST protocol defines data channels and control channels. The control channels are used to set up what data channels the sender and receiver use. Once the connection is established, data can flow continuously for delivering streaming data (Audio/Video). MOST provides point-to-point audio and video data transfer with a data rate of 24.8 Mb/s. Class D networks (speed over 1 Mb/s) is devoted to multimedia data (e.g., media-oriented system transport (MOST)).

3 Technical comparisons

In this section, we mainly analyze and compare the performance of the above automotive communication protocols, and provide some future perspective of automotive communication development. Table 2 compares the main characteristics of automotive protocols.

Table 2 Comparison of automotive protocols (partially from [3])

Automotive networking protocols				
	LIN	CAN	FlexRay	MOST
Classification	Class A	Class B & C	Class D	Class D
Application	Body & comfort	Powertrain, driver assistant control (High speed); body & comfort (Low Speed)	Chassis, driver assistance, safety control	Infotainment: stream data & control
Topology	Star, bus	Hieratical, bus	Bus, star, multi-star	Point-to-point
Media	Single wire	Twisted pair	Twisted pair or fiber	Optical
Bit encoding	NRZ	NRZ-5,MSb first	NRZ	BiPhase
Schedule approach	Time triggered	Event triggered	Time & event triggered	Event triggered
Media access	Master/slave	Contention	TDMA with priority	Master/slave
Error detection	8-bit CS	CRC	24-bit CRC	CRC
Header length	2Bits/Byte	11 or 29 Bits	40 Bits	Not specified
Data length	8 Bytes	0-8 Bytes	0-246 Bytes	Not specified
In message response	No	No	No	No
Bit rate	20Kb/s	10Kb/s – 1Mb/s	10Mb/s	25Mb/s
Maximum bus length	40m	Not specified, typical 40m	Not specified	Not specified
Maximum node	16	Not specified, typical 32	Not specified	24
Cost	Low	Medium	Medium	High

In the following, we give an example of automotive network architecture.

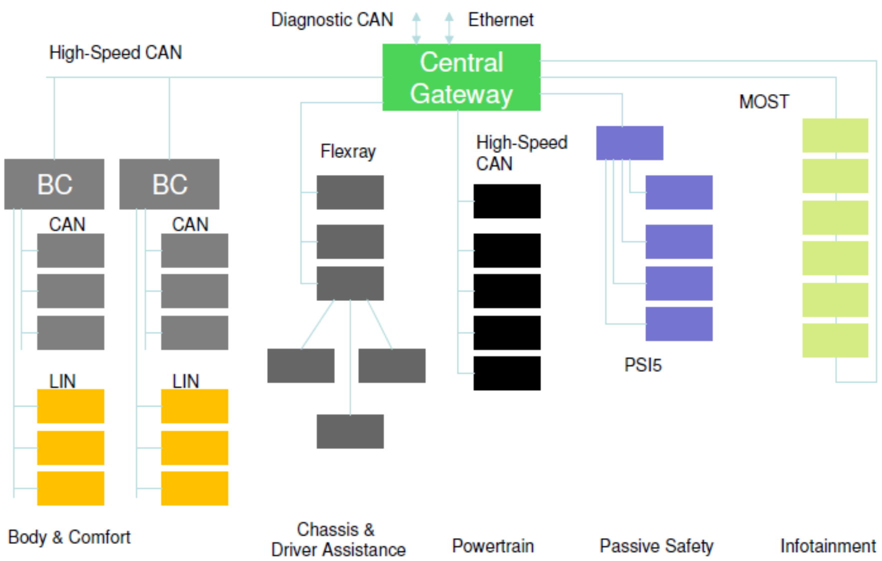

Figure 4 Automotive network architecture [8]

There are three classes of ECUs: powertrain and chassis, infotainment, and body electronics. Many of the ECU acronyms are defined in Figure 4. Several networks are used to connect the ECUs and the subsystems.
There are two CAN buses. One is for powertrain and the other CAN connects body electronics such as door and climate control. The FlexRay is used for chassis subsystems. A media oriented system transport (MOST) network defines networking for infotainment and telematics subsystems. It consequently connects ECUs for multimedia, phone, and antenna. Finally, local interconnect networks (LINs) are used to connect slave nodes into a subsystem for controlling body and comfort applications. The central electronic module (CEM) is an ECU that acts as a gateway between these buses. The maximum configuration for the vehicle contains about 40 ECUs.

It is common, in today's vehicles, that the electronic architecture include four different types of networks interconnected by gateways and up to 2500 signals (i.e., elementary information such as the speed of the vehicle) are exchanged by up to 70 ECUs.

At the end, we provide a roadmap of the automotive communication development in Figure 5. It is clear that the Ethernet technology will be a promising, universal and low cost solution for future automotive communications.

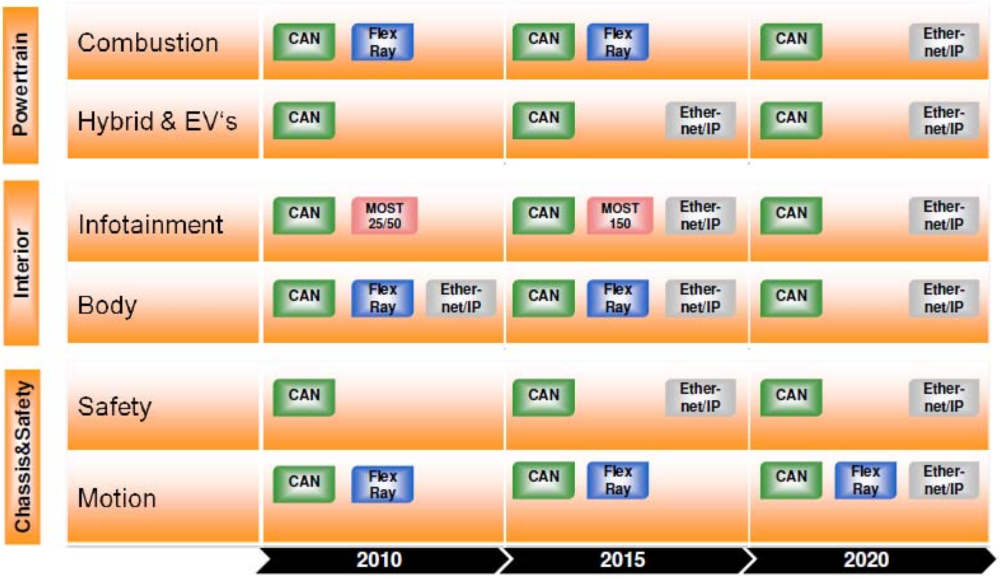

Figure 5 A roadmap of Automotive communication development [8]

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