COMMUNICATION & DATA PROTOCOLS FOR MOBILE EQUIPMENT

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BACKGROUND

As defined in the 2023 NFPA Technology Roadmap, there are many machine-level technology trends that are actively shaping the future of the fluid power industry. These trends include the increasing electrification, connectivity, and autonomous functionality of both the mobile and industrial machines that use fluid power in their power or control systems.

In September 2023, NFPA launched its Technology Task Force to better understand these trends, and to engage stakeholders across the supply chain in the development of the resources and connections that will be needed to keep fluid power positioned as an actuation technology of choice on mobile and industrial platforms.

The Task Force identified several projects that would help it fulfill this mission, including:

- **Communication & Data Protocols for Mobile Equipment.** Produce a white paper that summarizes the communications and data protocols most commonly used on mobile equipment. Collect and present case studies showing successful integrations with fluid power systems.

The Task Force met multiple times to discuss this project, to share information and resources, and develop a set of responses and recommendations. This is the report of the Task Force's final consensus, published on August 1, 2024.

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INTRODUCTION

This document is a summary of the various networks and communication protocols utilized currently in mobile equipment as well as future developments and potential technical advancements in this field.

At a high level, networks and communication protocols in this document refer to the various ways electronic devices "talk" to one another electronically onboard a mobile vehicle, also known as in-vehicle connectivity. These communication networks can either be wired or wireless and communicate over multiple different protocols for different application needs and requirements.

Communication protocols definition: A system of rules that allows two or more entities (devices) within an electronic system to transmit information via any variation of a physical quantity. The protocol defines the rules, syntax, semantics, synchronization, authentication, error detection and correction, and signaling. They are important because they create consistency and universality for the sending and receiving of messages over a network which may impact machine safety, reliability, robustness, and other factors. These protocols can be implemented in hardware, software, or very often, both.

STATE OF MOBILE INDUSTRY COMMUNICATIONS

While there are many types of networks and protocols available and currently in use, the mobile industry has primarily adopted CAN as a preferred network and SAE J1939 as the preferred protocol. The primary reason for the widespread use of CAN-J1939 is that diesel engine manufacturers adopted this on the engine ECU units beginning in the 1980s. Initially this was in the form of SAE-J1587 but due to speed limitations, it developed into SAE-J1939 by the early 2000s on top of the CAN 2.0 system created in 1991.

Since the vast majority of vehicles initially only had the engine ECU as the primary electronic component, and as OEMs wanted to reduce wiring costs without development effort, it made sense to adopt the engine protocol of SAE-J1939 into non-engine components for a cohesive in-vehicle communications system.

While CANbus network was developed by the automotive industry decades ago, and then the mobile industry adopted it in the 1980s, automotive companies have since implemented much faster and less expensive networks to meet the needs of changing and future applications in the market.

The adoption of wireless controls and wireless connectivity of vehicles has also expanded the range of networks and protocols.

These factors along with the growing application demand for AI, automation, safety, and efficiency have necessitated the review of what networks and protocols are best used for what applications in the mobile industry.

FUTURE TRENDS IN CONNECTIVITY

Technologies are ever evolving in the vehicle connectivity space. A multitude of vehicle networks and protocols are now being considered or used within the mobile industry as application needs and requirements change.

Below is an overview of the trends that are driving new considerations of the network and protocols.

1. **Functional safety.** Any safety-critical system within a vehicle typically must have functional safety built into it. Steer-by-wire, vision recognition, geo-fencing, and automation are a few of the trending technologies that are pushing the requirements for higher levels of safety in vehicles and thereby on the communications bus.

   a. **Definition of functional safety.** Refers to aspects of vehicle safety that pertain to the correct functioning of the system, vehicle, or device. Where failure or fault of a component, system, or vehicle can lead to severe consequences such as injury, death, or damage to property, it is crucial to implement some level of functional safety into this component, system, or vehicle.

   b. **For communications between devices**, IEC 61784-3 covers the transmission of safety-relevant messages and is in alignment with IEC 61508 for overall vehicle functional safety. Communications protocols that fall under this typically use a “black channel” to ensure functional safety while using an “unsecured” standard channel. For example, Ethernet is an unsecured standard protocol while Safety Over Ethernet is the functional safety version of the protocol that utilizes a black channel for fault checking. There are two SAE-J1939 protocol variants, but the main one is SAE-J1939-76 which implements checksums and sequence counters.

   c. **For reference** (DOES NOT DIRECTLY APPLY TO FUNCTIONAL SAFETY OF COMMUNICATIONS PROTOCOLS BUT TO FUNCTIONAL SAFETY IN GENERAL ON VEHICLES)

      Current state-of-the-art requirements for safety-critical functions in general on off-highway vehicles fall under:

      i. Standards to follow: ISO 13849 covers methodology, recommendations, and guidance for the design of machinery in safety-related parts of the control system including software.

ii. Standards to follow: ISO 25119 covers general principles for design and development of safety-related controls systems for tractors used in agriculture and forestry. Also can apply to self-propelled ride-on machines in agriculture.

iii. IEC 61508 Functional Safety Certification: This third-party certification includes industry-specific variants such as ISO 26262 for Automotive. IEC 61508 includes requirements based on Safety Integrity Level (SIL) and Automotive Safety Integrity Level (ASIL) which outline the level of fault tolerance the system or component needs to address and the corresponding SIL/ASIL level.

2. **Cybersecurity.** Another fast-evolving area that all stakeholders need to be aware of is cybersecurity for mobile machines. Most of the existing communications systems that are currently being used for mobile vehicles are not secure and would have expense related to making them secure against intrusion and hacking. The positive note is that vehicles that are not equipped with connectivity (telematics) are more immune to this issue since without remote access, a physical presence at the vehicle would be required. But the fast adoption of cellular connected systems presents significant challenges given the critical function many mobile vehicles serve in our mining, military, construction, and agriculture space.

    a. **Standard.** While on-road standards like ISO/SAE 21434 are currently being released for the automotive industry vehicle security, there are NO standards, unified approach, or coordination currently for off-highway vehicles. Best practice would be to understand and work with the ISO/SAE 21434 automotive standard and undergo a threat assessment for each vehicle platform to plan out a roadmap for adoption and implementation of key threat solutions.

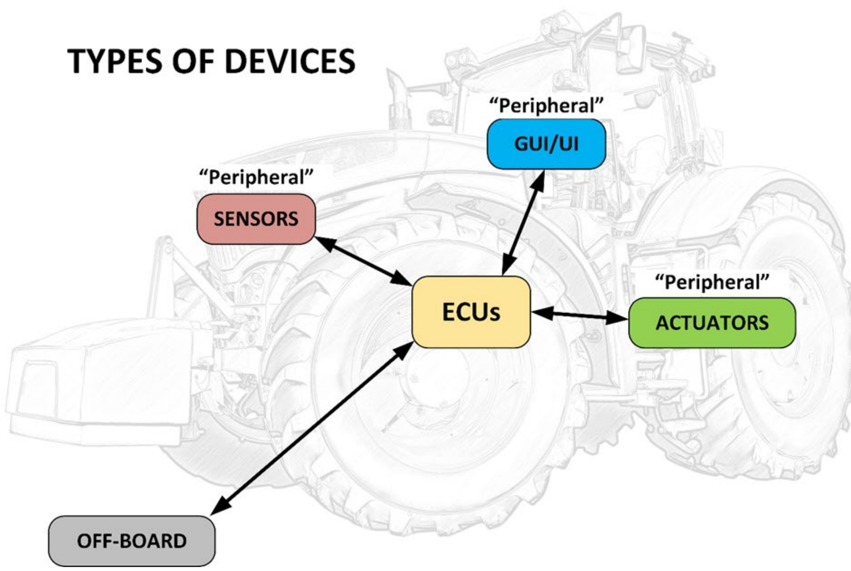
3. **Increased connectivity adoption.** The most obvious trend for communications of mobile vehicles is that there will be a continued acceleration in the adoption of connected vehicles requiring higher bandwidth for onboard and offboard communications.

TYPES OF DEVICES

There are five main types of devices onboard vehicles that communicate with each other:

1. **ECUs.** Electronic control units are devices that typically have microprocessors and can execute logic, math, or other advanced computational features. ECUs can both send and receive information to other ECUs and receive information from sensors. An industrial device that is analogous to this would be a PLC.

2. **Sensors.** Sensors are devices that produce an output signal for the purpose of detecting a physical phenomenon. Typical sensors include position, temperature, distance, voltage, current, angle, or light. But there are thousands of types of sensors. Sensors also can include vision, ultrasound, or radar. Some but not all types of sensors include digital (two states, i.e., either ON or OFF), analog (proportional signal), or "smart" sensors. Smart sensors typically refer to a sensor that has an onboard microprocessor and can communicate bidirectionally through a protocol like CANbus.



3. **Actuators.** In this document, refers to an electronically controlled component that produces a force, torque, or displacement.

4. **GUI/UI.** User interfaces and graphical user interfaces are devices that the operator of the vehicle interfaces with. These typically are buttons, knobs, joysticks, switches, displays, and touchscreens. Like sensors, these can be "digital", "analog", or "smart".

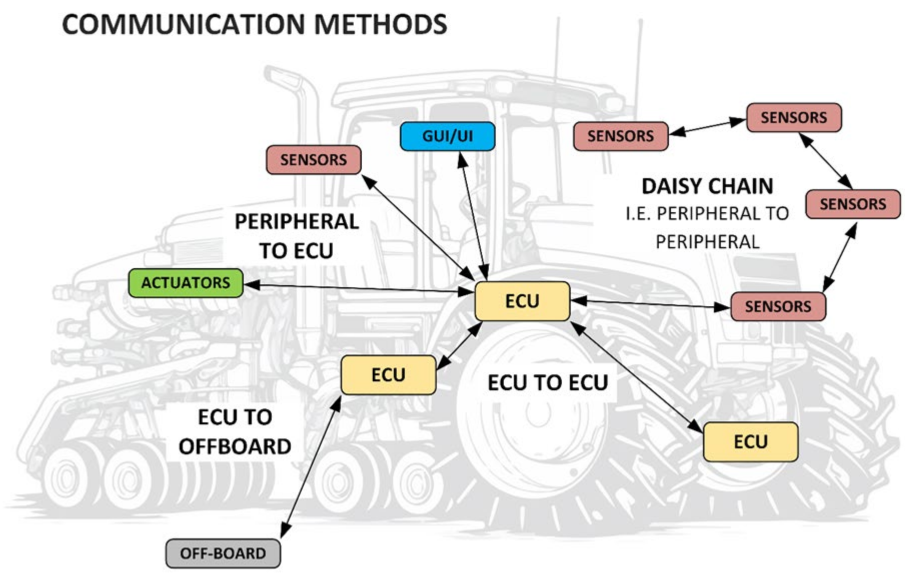
5. **Offboard/External.** These devices are not a permanent part of the vehicle and can be connected either wired or wireless. For example, an external PC connected via USB, Ethernet, Cellular, or WiFi. These types of devices include smart phones, tablets, portable data acquisition systems, or external computers.

COMMUNICATION METHODS

Each type of device depending on its requirements, location, and function can communicate in various ways. For various reasons (reduce wiring expense, improve functionality, increase data speed, etc.) several methods of hardware and software communication protocols have been developed. Here are four prevalent methods:

1. **Daisy Chain (Peripheral to Peripheral).** The sensors and other peripherals are typically the most numerous and therefore the most expensive to implement in terms of wiring. There are also many levels of resolution and speed that may be required that have allowed lower cost protocols to be implemented for this category.

2. **Peripheral to ECU.** When dedicated lines of communication are needed for either speed, safety, redundancy, or bandwidth, there are specific protocols for this arrangement.



3. **ECU to ECU.** When communications are between ECUs on the vehicle, there is often the need for high levels of reliability, high speed or bandwidth, functional safety, noise immunity, or other higher performance or added features. This level of communication has led to the development of new protocols for this purpose.

4. **ECU to Offboard.** When communicating from the vehicle to an off-board device, there are often few constraints since the connection is typically temporary and not required to withstand the operating environment of the vehicle application. Therefore, there are different protocols that have been developed for this method.

TYPES OF MOBILE COMMUNICATION PROTOCOLS

Protocol	Description	Speed	Safety Features	System	Application	Cost
SENT	Single Edge Nibble Transmission	25 Kbits/s		2-wire	P2P	$
LIN	Local Interconnect Network	19.2 Kbits/s		Single Wire	P2P	$
PSI5	Peripheral Sensor Interface	125 Kbits/s		Twisted pair	P2P	$
FLEXRAY	Being phased out	10 Mbits/s	Deterministic Safety critical devices	2 or 4 wires or optical	E2E	$$$
AUTOMOTIVE ETHERNET	LAN network	1 Gbits/s	Time Triggered Deterministic Safety critical devices	Twisted pair or optical	E2E	$$$$
CAN-J1939	11 and 29 bit	250 Kbits/s 500 Kbits/s		Twisted Pair	P2P E2E	$$
CAN Open	11 and 29 bit	1,000 Kbits/s		Twisted Pair	P2E	$$
CAN FD	Flexible Data rate	8 Mbits/s		Twisted Pair	E2O	$$
Bluetooth	Short Range	3 Mbits/s		Wireless	Vehicle to cloud	$
UWB	Short range	100 Mbits/s				$
ZigBee	Short range	250 Kbits/s				$
WiFi	Medium range	54 Mbits/s			Vehicle to device	$
Cellular (C-V2X)	Long range	50 Mbits/s				$$
WiMax	Long range	6 Mbits/s				$$$
Vehicle to Offboard – Data Acquisition / Real Time						
XCP	CANbus	See Above	N/A	See Above	Vehicle to DAQ	
	Ethernet					
	UDP					
	UART					
POTENTIAL FUTURE ADOPTION / MIGRATION						
EtherCAT	Low latency / LAN	100 Mbits/s	Time Triggered Deterministic Safety critical devices	2 wire	E2E	

P2P – Peripheral to Peripheral / E2E – ECU to ECU / E2O – ECU to Offboard / P2E - Peripheral to ECU

PROS AND CONS OF MOBILE COMMUNICATION PROTOCOLS

Protocol	Pros	Cons
SENT (Single Edge Nibble Transmission)	• Simple, lightweight protocol suitable for sensors and actuators. • Low latency and deterministic behavior. • Reliable transmission over noisy environments.	• Limited bandwidth and payload size. • Unidirectional communication. • Not suitable for complex data transmission or high-speed applications.
LIN (Local Interconnect Network)	• Low-cost solution for communication between electronic control units (ECUs) in vehicles. • Simple and easy to implement. • Supports master-slave communication topology.	• Limited bandwidth and speed compared to other protocols. • Unidirectional communication. • Not suitable for high-speed or complex data exchange.
PSI5 (Peripheral Sensor Interface)	• Optimized for automotive sensor applications. • Provides synchronous data transmission for accurate sensor readings. • Supports high reliability and fault tolerance.	• Limited adoption compared to other protocols. • Restricted to sensor interface applications. • Relatively complex implementation compared to other protocols.
FlexRay	• High bandwidth and deterministic communication suitable for real-time applications. • Supports redundant communication channels for fault tolerance. • Designed for complex data exchange in modern vehicles.	• Higher implementation complexity and cost. • Limited adoption compared to other protocols. • Requires specialized hardware and expertise.
Automotive Ethernet	• High-speed, scalable communication suitable for bandwidth-intensive applications. • Supports complex data exchange for advanced driver assistance systems (ADAS) and infotainment. • Enables integration with standard Ethernet networks.	• Higher cost compared to traditional automotive protocols. • Requires reliable network infrastructure for optimal performance. • Vulnerable to cybersecurity threats without proper security measures.
CAN-J1939	• Standardized protocol widely used in heavy-duty and commercial vehicles. • Robust and reliable communication over noisy environments. • Supports vehicle diagnostics and control applications.	• Limited bandwidth compared to newer protocols. • Not ideal for high-speed or bandwidth-intensive applications. • Limited flexibility for real-time data exchange.
CAN Open	• Open-source protocol widely used in industrial and automotive applications. • Supports standardized device profiles for interoperability. • Enables plug-and-play functionality for networked devices.	• Limited bandwidth and speed compared to newer protocols. • Requires additional overhead for message arbitration and addressing. • Not suitable for high-speed or time-critical applications.

Protocol	Pros	Cons
CAN FD (Flexible Data-Rate)	• Enhanced version of CAN with higher data rates and larger payload sizes. • Suitable for applications requiring increased bandwidth and throughput. • Backward compatible with existing CAN networks.	• Limited adoption compared to traditional CAN. • Increased complexity in hardware and software implementation. • Higher cost compared to standard CAN.
Bluetooth	• Widely adopted wireless protocol for short-range communication. • Low power consumption and seamless connectivity. • Supports various profiles for audio streaming, hands-free calling, and data transfer.	• Limited range compared to other wireless protocols. • Lower data transfer rates compared to Wi-Fi. • Vulnerable to interference in crowded wireless environment.
UWB (Ultra-Wideband)	• High data transfer rates over short distances. • Precise location tracking and positioning capabilities. • Low power consumption and resistance to interference.	• Limited range compared to other wireless protocols. • Higher implementation cost. • Limited adoption in automotive applications compared to other protocols.
ZigBee	• Low power consumption and low data rates suitable for sensor networks and home automation. • Mesh networking capability for extended coverage and robustness. • Standardized protocol with interoperability between devices from different manufacturers.	• Limited bandwidth and data transfer rates compared to other protocols. • Limited range compared to other wireless protocols. • Higher latency compared to some other wireless protocols.
Wi-Fi (IEEE 802.11)	• High data transfer rates and range suitable for in-car Wi-Fi hotspots and multimedia streaming. • Wide availability and compatibility with existing infrastructure. • Supports seamless connectivity with smartphones and other devices.	• Higher power consumption compared to other wireless protocols. • Vulnerable to interference in crowded wireless environments. • May require additional security measures to prevent unauthorized access.
Cellular (C-V2X)	• Wide coverage area and high-speed connectivity suitable for telematics, remote diagnostics, and over-the-air updates. • Enables vehicle-to-everything (V2X) communication for advanced safety and autonomous driving applications. • Continuously evolving network infrastructure with improvements in speed and reliability.	• Requires subscription plans and ongoing service fees. • Relatively higher latency compared to other wireless protocols. • Vulnerable to network congestion and signal attenuation in remote areas.

Protocol	Pros	Cons
WiMax	• Long-range wireless broadband connectivity suitable for wide-area networks. • High data transfer rates and scalability for various applications. • Supports mobility and seamless handover between base stations.	• Limited adoption and infrastructure compared to other wireless protocols. • Higher implementation cost compared to Wi-Fi and cellular. • Limited availability of compatible devices and equipment.
XCP (Universal Measurement and Calibration Protocol)	• Standardized protocol for real-time measurement, calibration, and diagnostics of ECUs. • Efficient access to internal parameters for testing and calibration purposes. • Supports high-speed data transfer and synchronization with measurement tools.	• Requires specialized tools and expertise for implementation. • Limited support for network communication compared to other protocols. • May require additional security measures to prevent unauthorized access.

END MARKET APPLICATIONS OF MOBILE COMMUNICATION PROTOCOLS

Protocol	Construction	Agriculture	Mining	Military
LIN (Local Interconnect Network)	Basic control functions, sensor monitoring, and simple diagnostic applications.	Basic control functions, sensor monitoring, and simple diagnostic applications.	Basic communication between vehicle subsystems, interior controls, and basic monitoring functions in mining equipment.	Basic communication between vehicle systems, interior controls, and non-critical vehicle functions in military vehicles.
PSI5	Basic sensor interfaces, interior controls, and low-speed communication between vehicle subsystems.	Basic sensor interfaces, monitoring of environmental parameters, and low-speed communication in agricultural machinery.	Basic sensor interfaces, monitoring of equipment status, and low-speed communication in mining vehicles and equipment.	Basic sensor interfaces, monitoring of vehicle subsystems, and low-speed communication in military vehicles and equipment.
Automotive Ethernet	Advanced vehicle control systems, telematics, and fleet management applications.	Precision farming systems for data-intensive applications such as GPS guidance, automated steering, and real-time monitoring.	Remote monitoring and control of heavy machinery, asset tracking, and predictive maintenance systems.	Communication between onboard systems, surveillance, and command and control applications.
CAN-J1939	Engine control, transmission control, hydraulic controls, and vehicle diagnostics.	Control of implements, monitoring sensor data, engine control, and implementing precision agriculture applications.	Engine control, transmission control, hydraulic controls, and vehicle diagnostics.	Communication between vehicle systems, weapon systems, and onboard electronics.
CAN Open	Vehicle control systems, hydraulic controls, and onboard diagnostics for reliable communication between components and subsystems.	Precision agriculture equipment for controlling implements, monitoring sensor data, and implementing automated guidance systems.	Engine control, transmission control, and condition monitoring applications.	Communication between vehicle subsystems, weapon systems, and onboard electronics.
CAN FD (Flexible Data-Rate)	Integrated into vehicle control systems, hydraulic controls, and onboard diagnostics for real-time data exchange and fault detection.	Controlling implements, monitoring sensor data, and implementing automated guidance systems.	Engine control, transmission control, and condition monitoring applications.	Communication between vehicle subsystems, weapon systems, and onboard electronics.

Protocol	Construction	Agriculture	Mining	Military
Bluetooth	Onboard entertainment systems, hands-free communication, and diagnostic tools for wireless connectivity.	Wireless data transfer between sensors, controllers, and mobile devices.	Wireless communication between operators, supervisors, and equipment monitoring systems in underground and surface mining operations.	Short-range communication between personnel, vehicles, and handheld devices in tactical environments.
UWB (Ultra-Wideband)	Precise location tracking of personnel, assets, and equipment on construction sites.	Accurate positioning and tracking of agricultural machinery, automated guidance systems, and crop monitoring applications.	Personnel tracking, asset management, and safety monitoring in underground mining operations.	Indoor positioning, asset tracking, and situational awareness in military facilities and urban environments.
ZigBee	Wireless sensor networks, remote monitoring, and control of automation systems.	Wireless sensor networks, environmental monitoring, and precision agriculture applications.	Wireless sensor networks, personnel tracking, and environmental monitoring in mining operations.	Wireless sensor networks, perimeter security, and environmental monitoring in military installations and facilities.
Wi-Fi (IEEE 802.11)	Onboard entertainment systems, telematics platforms, and site-wide Wi-Fi networks for communication and data exchange.	Wireless data transfer between field sensors, machinery, and management systems for real-time decision-making and precision agriculture applications.	Communication between equipment operators, supervisors, and central control systems, as well as for real-time monitoring of equipment health and performance.	High-bandwidth communication between vehicles, command centers, and deployed personnel, as well as for streaming video and data from remote sensors and drones.
Cellular (C-V2X)	Fleet management systems, remote diagnostics, and telematics platforms for real-time monitoring and asset tracking.	Remote monitoring of equipment, precision agriculture applications, and data exchange between farm machinery and cloud-based platforms.	Remote monitoring of equipment health, predictive maintenance, and communication between mobile assets and central control systems.	Communication between vehicles, command centers, and deployed personnel, as well as for remote surveillance and reconnaissance.

Protocol	Construction	Agriculture	Mining	Military
WiMax	High-speed wireless broadband connectivity at construction sites, remote offices, and temporary work locations.	Broadband internet access, remote monitoring, and data exchange in rural agricultural areas with limited wired infrastructure.	High-speed data communication between mining sites, central offices, and remote operations.	High-bandwidth communication between military installations, command centers, and deployed personnel in remote areas.
XCP (Universal Measurement and Calibration Protocol)	Vehicle diagnostics tools, calibration equipment, and data acquisition systems for testing and validation of vehicle subsystems.	Vehicle diagnostics, calibration of agricultural machinery, and real-time monitoring of sensor data.	Equipment diagnostics, calibration of mining machinery, and real-time monitoring of critical parameters.	Vehicle diagnostics, calibration of military vehicles, and real-time monitoring of performance parameters in military applications.
EtherCAT	Real-time control of automation components, motion control, and data acquisition applications.	Controlling agricultural machinery, monitoring sensor data, and implementing automated control systems.	Real-time control of mining equipment, conveyor systems, and material handling operations.	High-speed data acquisition, control systems, and real-time monitoring of critical equipment and processes in military applications.

GLOSSARY OF TERMS

Automotive Ethernet: A high-speed, Ethernet-based communication protocol increasingly used in modern vehicles for high-bandwidth applications such as advanced driver assistance systems (ADAS), infotainment, and vehicle-to-everything (V2X) communication.

Baud Rate: The speed at which data is transmitted over a serial communication link, typically measured in bits per second (bps).

Bluetooth: A wireless technology standard for exchanging data over short distances between fixed and mobile devices. It's commonly used in vehicles for hands-free calling, audio streaming, and data transfer between smartphones and in-car systems.

Bus Off: A state in which a node on a CAN bus is unable to communicate due to errors or faults, typically resulting in disconnection from the bus.

CAN (Controller Area Network): A robust vehicle bus standard designed to allow microcontrollers and devices to communicate with each other within a vehicle without a host computer.

CAN Bus Arbitration: The process by which multiple nodes on a CAN bus contend to transmit messages based on priority, determined by the message identifier.

Cellular (LTE, 5G): Cellular network standards such as LTE (Long-Term Evolution) and 5G are increasingly used in vehicles for connected services, telematics, and remote diagnostics. They enable high-speed internet connectivity and communication with cloud-based services.

Checksum: A value calculated from the data transmitted to detect errors in transmission, typically added to the end of a message frame.

Diagnostic Trouble Code (DTC): An alphanumeric code stored in a vehicle's computer system that indicates a problem or malfunction within the vehicle.

DSRC (Dedicated Short-Range Communications): A wireless communication protocol designed for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, primarily for safety applications such as collision avoidance and cooperative adaptive cruise control.

DLC (Data Length Code): A field in CAN messages that specifies the number of bytes of data contained within the message frame.

ECU (Electronic Control Unit): A microcontroller-based system within a vehicle responsible for controlling various electrical systems and subsystems.

FlexRay: A high-speed automotive network communications protocol designed to handle complex data communication in modern vehicles.

Frame: A unit of data transmission in a communication protocol, consisting of a header, data payload, and possibly a checksum for error detection.

Gateway: A device or software component that acts as an interface between different communication protocols or networks within a vehicle.

LIN (Local Interconnect Network): A low-cost, serial communication protocol used for communication between components in vehicles.

LIN Master/Slave: Devices within a LIN network where the master node initiates communication and controls the data flow, while slave nodes respond to commands from the master.

MOST (Media Oriented Systems Transport): A high-speed multimedia network protocol used in vehicles to transport audio, video, and control data between various multimedia components.

OBD (On-Board Diagnostics): A standard protocol used to retrieve diagnostic information from a vehicle's computer systems, typically through a connector located under the dashboard.

SAE J1939: A standard used for communication and diagnostics among vehicle components, primarily heavy-duty and commercial vehicles.

UDS (Unified Diagnostic Services): A diagnostic communication protocol used in automotive systems to communicate with electronic control units (ECUs) in the vehicle.

Wi-Fi (IEEE 802.11): A wireless networking technology that allows devices to communicate wirelessly over short distances. In vehicles, it's used for in-car Wi-Fi hotspots, over-the-air updates, and wireless streaming of audio and video content.

XCP (Universal Measurement and Calibration Protocol): A standardized protocol used for measurement, calibration, and diagnostics of electronic control units (ECUs) in vehicles. XCP enables efficient and real-time access to ECU internal parameters for testing and calibration purposes.

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