The Inevitable – Ethernet in Automotive

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Abstract
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The automobile industry is at the biggest inflection point it has ever seen. Cars are transitioning to clean, electric systems, the field of artificial intelligence is witnessing major leaps through deep learning and powerful processing engines. Suddenly the possibility of self-driving vehicles is becoming a reality, not just some science fiction dream. Legislators, car manufacturers and various types of technology providers all play a key role in this automotive revolution but the road to a safe, autonomous transportation solution may be more dependent on the In-Vehicle Network (IVN) developers than any other stakeholder.

In this whitepaper we discuss the requirements for the next generation of IVNs and why Ethernet is the ideal solution. It will delve into why the speed requirements are so high for autonomous vehicles and the factors driving those requirements. What this amounts to is effectively a data center on wheels, bringing with it both challenges and opportunities, as innovative players race to develop the next-generation of IVNs.

The inherent technical advantages which make Ethernet the preferred choice for self-driving vehicles will also be covered. Ethernet has a rich history of supporting numerous proven technologies and standards that can easily balance functionality and cost to deliver the required features at any price point. In addition, this white paper will discuss some misconceptions about Ethernet with respect to automotive networking.

Finally, there will be a discussion on the current use of Ethernet in IVNs, and what the automotive industry anticipates for Ethernet in the future. Ethernet’s ubiquity, vast developer ecosystem, interoperability, and compatibility with numerous devices plus its ability to support other mediums makes it the preferred choice for autonomous vehicles IVNs, heralding a new and exciting era for the automotive industry and Ethernet as a whole.
Preface

A revolution in the automotive industry is upon us. Fifteen years ago, the very thought of a commercial showing a self-driving car was science fiction. While companies like Waymo have performed wide-scale experiments with hundreds of cars in field trials, proving that autonomous vehicles are possible, the assumption was that it would take 15 to 20 years to become a mature technology. As time passes, people are starting to realize that this revolution will happen sooner rather than later. The investments that companies are making in autonomous vehicles are gigantic. Legislation is also under way to create the legal and regulatory framework for autonomous driving.

Still, the biggest barrier to commercially available autonomous vehicles is trust, or more accurately the mistrust humans have in machine-driven vehicles. According to the National Safety Council (NSC), there are over 100 fatal accidents per day in the US. This hardly ever makes headlines. However, a single Tesla or Uber accident makes the front page, and everyone gets nervous. People ignore the small print in the National Highway Traffic Safety Administration (NHTSA) accident report on Tesla that states that the first year that Tesla AutoPilot (auto-steering) was introduced, the number of accidents with Tesla vehicles dropped by 40%! This was even before the additional improvements Tesla did in this system, after this feature became commercially available. The US Department of Transportation estimates that autonomous vehicles could reduce traffic fatalities by 94% by eliminating accidents due to human error.

To truly gain people’s trust in machine-driven cars, autonomous car systems have to be extremely reliable. It starts with the brain of the system, which is the SoC/GPU running Artificial Intelligence (AI) programs to accurately analyze the 360-degree view around the car and define the right driving policy. It extends to the eyes and ears of the car, which are the cameras and other sensors. These cameras and sensors need to work reliably in every extreme condition whether at night, in bad weather, or at extremely high temperatures.

The next big challenge is to build the nervous system that connects everything. This is the In-Vehicle Network (IVN) that carries data reliably between the different nodes of the network and to provide the redundancy that delivers a system with no failures.

In addition, with the Autonomous-driving Level moving from Level 1-2 to Level 3-4 – with Level 5 on the horizon – the speed of the IVN and its complexity are growing in parallel, as shown in Figure 1.

The biggest barrier to commercially available autonomous vehicles is trust. In-Vehicle Networks (IVN) should provide the redundancy that delivers a system with no failures.
While Level 1-2 vehicles with Advanced-Driver Assistance Systems (ADAS) include one to three low-resolution cameras together with a basic controller that makes minimal decisions, mainly for braking and velocity, the system for a Level 4-5 vehicle is more like a data center on wheels. Level 4-5 systems will have anywhere from 10 to more than 20 cameras and sensors, plus a few centralized computing systems that will be responsible for everything including vision analytics, driving policy, high bandwidth telematics, advanced storage systems. All these nodes need to be connected with a reliable network that can provide the speed, quality-of-service (QoS) and security levels that are expected in autonomous vehicles.

Over the last thirty years, many protocols and solutions have been developed for the IVN based on the requirements of Level 1-2 cars. A few new protocols, which are mostly proprietary, were introduced in the last few years with the goal of providing a solution for future Level 3-4-5 cars. Once the market identified the requirements and complexity of the network for future cars, many OEMs and Tier-1s recognized that Ethernet had the highest potential to meet all the needs for these networks.

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In this paper, we will discuss the requirements of the IVN and why many OEMs believe that Ethernet will eventually be the ultimate solution for IVNs in autonomous vehicles. These topics are covered in the following chapters:

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The Need for Higher Speed

Simply put, increased sensor bandwidth is driving the speed of IVNs. The main applications for a high-speed network in a car are cameras and sensors. Cameras are now upgrading from resolutions of 720p to 1080p, and even up to 4k. In addition, the pixel size (color depth) has increased to 16, 20, and even 24 bits per pixel. The result is that the required data bandwidth to carry the high-resolution video is growing. As shown in the table on the left-side of Figure 2, where 1Gbps used to be sufficient, there are now many use cases that require 2.5, 5 and even 10Gbps of raw sensor data rate.

The use of raw data is a change for many high-bandwidth automotive sensors. In general, today’s existing high-bandwidth sensor modules such as cameras, lidar, etc., integrate a pre-processing IC to reduce the data bandwidth output. However, with the latest generations of high-compute power SoCs/GPUs, which can now process the raw data from the sensors, the new trend is to eliminate the pre-processing units, for the following main reasons:

- Remove the latency created by the pre-processing or the compression algorithms
- Prevent the loss of picture quality created by compression, which can lead to wrong decisions being made by the system
- Reduce the cost of the sensor module
- Reduce the heat dissipation in the sensor modules, which greatly affects the performance of the sensors

The result is that the network now needs to transport the raw data from these sensors anywhere at a rate between 2 to 8Gbps. This speed is expected to continue increasing in the future.

Cameras

Increasing resolution from 720p to 4K and improving dynamic range = Multi-Gigabit/s of raw bandwidth

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Sensor Fusion

Moving processing of data from sensors to a centralized GPU = Multi-Gigabit/s data over the network

Cameras are now upgrading from resolutions of 720p to 1080p, and even up to 4k. 1Gbps used to be sufficient, but there are now many use cases that require 2.5, 5 and even 10Gbps of raw sensor data rate.
In addition to the needs of the sensors, other modules require a network connectivity with high bandwidth. For example, the telematics module that connects the car to other cars (V2V) and to the cloud (V2I) are required to support increased data rates. Today, the telematics module generates less than 1Gbps of traffic, but in autonomous cars it is expected to deliver a few gigabits of traffic to the system’s central CPUs. Finally, data storage on the vehicle is another system that will also require a high bandwidth network.

As will be discussed later, Ethernet is a natural choice because its protocols and drivers have already shown it can provide flexible, cost-efficient, reliable networks at these speeds in a variety of computing applications.

**The Complexity of Next-Generation IVNs**

While today’s typical mid-/high-end cars have about twenty Electronic Control Units (ECUs), by 2020 high-end cars will have more than 100 ECUs, and autonomous vehicles will integrate more than 200 ECUs. In addition, the number of cameras and sensors are anticipated to grow to more than 20 per car.

Different OEMs use different methodologies and architectures to build the network inside the car, including the number and type of domains, and the network solution for each domain. Still, the most important concept shared by all for autonomous vehicles is the uncompromising requirement for the highest levels of reliability, especially in the ADAS system. Without diving into detailed definitions of functional safety specifications, the basic requirement from the system is to have no major failures, considering that individual components of the network can and will – fail this is by far an over simplification of the functional safety requirements, but is sufficient for the point that we need to make here.

To achieve the goal of avoiding any major failure, the system needs to have enough redundancy for all the mission-critical systems. This redundancy can be achieved using “networking” and the capability to transfer data between nodes over different paths.

This redundancy can be achieved in various ways, and they are all related to the concept of “networking” and the capability to transfer data between nodes over different paths. Figure 3 shows a basic network topology for the ADAS system, which is a simplified version of the existing and the future proposed networks.

This diagram shows two central units (GPU/CPU), that are connected to all the cameras and sensors over a network of three switches. The data from the cameras and sensors are sent to the central unit that controls the car, while the other central unit is used as a backup that will take control over the car in case the first unit fails. The network sends the data from the cameras and sensors to either or both of the central units, based on the system configuration, which can also change dynamically according to the situation.
In addition to the ADAS systems the network needs to support other domains and applications such as storage, gateways, telematics and more, that all need to be connected by the IVN and work reliably under the demanding conditions of the car environment.

Another important concept of the network for an autonomous car is the ability to maintain the level of security that prevents malicious attacks of human origin from external systems aiming to remotely control the car, prevents disclosure of confidential data, and otherwise prevents data hacking. An additional important attribute of the secured system is to maintain the availability and integrity of critical systems such as sensors and prevent malicious manipulation of sensor or control data. Attacks on the communications network can occur in the form of deliberately inserted faulty messages (such as accelerating or braking commands) or intentional interference with the transmission of correct messages (such as masking important messages between control systems).

There are various methods and layers to protect the network—a level of detail that is beyond the scope of this paper. But at a basic level, the network needs to include the means to encrypt and decrypt the data, as well as providing point-to-point security on links between nodes that are directly connected and the ability to identify and prevent intrusion—something that is also referred to as “man-in-the-middle” attacks. Again, Ethernet networks have a well-established history of providing this security and redundancy for widespread network applications.

In the next two sections, we will discuss in more detail the features that make up the Ethernet standard and are essential for next generation car networks, as well as some misconceptions about Ethernet in automotive. These sections include many technical details. If there is no interest in reading the technical details, feel free to skip to the chapters titled “Why Ethernet Has Always Won” and “Ethernet in IVN, and Where It’s Going Next”.

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Figure 3: In-Vehicle Network (IVN) for ADAS

- Switch with Multiple PHYs
- Controller
- PHYs/Bridges
- Ethernet link – 2.5 / 5 / 10G
- Ethernet link – 25G
- Radar, Lidar, Sonar
- Camera
Advantages of Ethernet for Automotive

Ethernet standards comprise a long list of features and solutions that have been developed over the years to resolve real network needs or resolve threats. Developers of Ethernet IVNs can easily balance between functionality and cost by picking and choosing the specific features they would like to have in their car network. In this section, we will discuss some of these common features. Figure 4 shows the Ethernet technologies that benefit IVN.

Switching

The essence of a network is that it is all about addressing and switching – the capability to send data between specific nodes that share the same network. One of the most important attributes of Ethernet network/switching is the capability to send the traffic between two nodes over different routes in the network.

Addressing devices and switching through multiple routes is what provides the redundancy that is critical for the functionality and reliability of the IVN. The architecture of the Ethernet Local Area Network (LAN) is based on the IEEE 802.1 standard that defines internetworking among 802 LANs, link security, overall network management, and the higher protocol layers above Media Access Control (MAC) and Logical Link Control (LLC). The IEEE 802.3 standard defines the MAC and the Physical Layer (PHY) of the network.

Ethernet switching naturally creates another very important benefit for the IVN: the ability to define a wide range of network topologies.

Developers of Ethernet IVNs can easily balance between functionality and cost by picking and choosing the specific features they would like to have in their car network.
Ethernet supports almost any of the network topologies including mesh, star, ring, daisy-chain, tree and bus (as shown in Figure 5). This allows system and domain developers to choose the optimal topology for each domain, while leveraging the same basic components.

**Ethernet PHY Speeds**

The first IEEE standard for Automotive Ethernet PHY was the 100BASE-T1 (100Mbps) that was developed under 802.3bw, which was ratified in 2015, for 100Mbps Ethernet on single-pair, unshielded automotive cable.

Soon after, the next generation of 1000BASE-T1 PHY (1Gbps) specifications were developed under 802.3bp and ratified in 2016. 100BASE-T1 has been adopted by many OEMs and most of the luxury cars today use 100M Ethernet networking. The 1000BASE-T1 PHY products were introduced to the market in 2017 and will be in mass production by 2020.

The latest Automotive Ethernet PHY standard development for 10Gbps, as well as 2.5Gbps and 5Gbps, is in development under the IEEE 802.3ch Task Force, and draft 1.0 is expected by the end of 2018.

**Figure 5: Ethernet Supports All Topologies**

The payload size of data packets sent over Ethernet is variable, allowing maximum flexibility for carrying different types of application loads. In addition, Ethernet’s native support of broadcast and multicast allows high efficiency, with low latency for each of these topologies.

Ethernet MAC supports rates of 10Mbps, 100Mbps, 1Gbps, 2.5Gbps, 5Gbps, 10Gbps, 25Gbps, 50Gbps, and soon 100Gbps. These MAC rates open the door for future automotive network speeds beyond 10Gbps.
Ethernet MAC Speeds

IEEE 802.3 developed standards for MAC at rates ranging from 10Mbps all the way up to 100Gbps (200Gbps and 400Gbps were also developed, but these rates today require multiple channels of 100Gbps).

Specifically, Ethernet supports rates of 10Mbps, 100Mbps, 1Gbps, 2.5Gbps, 5Gbps, 10Gbps, 25Gbps, 50Gbps, and soon 100Gbps – developed under 802.3ck. These MAC rates open the door for future automotive network speeds beyond 10Gbps.

Asymmetrical Ethernet

Ethernet is fully symmetrical, meaning it can transport data at the same speed in both directions on the single-pair automotive cable. This capability makes it the preferred technology for the network backbone.

However, Ethernet can also operate in an asymmetrical mode when needed, by using the protocols of Energy Efficient Ethernet (EEE). In the normal mode of operation, the Ethernet link consumes power even when a link is idle, and no data is being transmitted. EEE provides a method to reduce power consumption during periods of low data activity in either or both directions. EEE is based on the IEEE 802.3az standard and uses a Low Power Idle (LPI) mode to reduce the energy consumption of a link when no packets/data are being sent.

The standard specifies a signaling protocol to achieve power saving during idle time by exchanging LPI indications to signal the transition to low-power mode when there is no traffic. LPI indicates when a link can go idle, and when the link needs to resume after a predefined delay without impacting data transmission. For example, when used over a single-pair automotive cable, connected to a camera, the link from the SoC/GPU to the camera – that is used for camera controls – can be set to EEE mode, with short data bursts, for power saving.

A new proposal is under discussion in IEEE 802.3ch, for special EEE modes that can be useful on highly asymmetric links and can help reduce power even further in automotive applications.

Virtual Local Area Network (VLAN)

VLAN works by applying 802.1Q tags to network packets and handling these tags in networking systems – creating the appearance and functionality of network traffic that is physically on a single network, but acts as if it is split between separate networks. This way, VLANs can keep traffic from different applications on nodes separate, despite being connected to the same physical network. VLANs also allow grouping of nodes and data sources together even if they are not directly connected to the same switch. Because VLAN membership can be easily configured, system design and node and data source deployment are greatly simplified.

VLAN traffic can be routed, multicast and broadcast. In addition, VLANs also support Quality of Service and traffic prioritization using the 802.1P standard, allowing efficient bandwidth utilization.
Precision Time Protocol

The vision analysis algorithm in a car requires either simultaneous sampling of multiple sensors or knowing the time that a measurement was taken. As these measurements are taken by different sensors and cameras, and carried through different routes, (cables, repeaters, hubs, and switches), time synchronization needs to be done between all the nodes in the car down to very short time intervals (in the range of 0.5 microseconds).

The IEEE 802.1AS (Timing and Synchronization for Time-Sensitive Applications in Bridged Local Area Networks) standard allows for synchronization of timing. This standard leverages the IEEE 1588 v2 and uses a special profile called “PTP Profile” to select the best clock source in the system as the master clock for all nodes. Additionally, clock redundancy and rapid failover is easily supported using these protocols.

Audio Video Bridging (AVB/TSN)

Audio Video Bridging (AVB) is a method to transport audio and video (AV) streams over Ethernet-based networks. AVB is based on IEEE standards for Ethernet networks that define signaling, transport, and synchronization of the audio and video streams. In essence, AVB works by reserving a fraction of the available Ethernet bandwidth for AVB traffic. Its main attributes for Ethernet networks include:

- Precise timing of streaming in conjunction with PTP. Support of low-jitter media clocks and accurate synchronization of multiple streams.

- A reservation protocol that enables the endpoint device to notify the various network elements to reserve resources necessary to support its stream.

- Queuing-and-forwarding defined rules to ensure that an AV stream will pass through the network within the delay specified in the reservation.

These attributes dictate the Quality-of-Service of the network. The IVN driver assistance systems rely on AV bridging to get data from cameras and sensors in a timely manner, at a low, controlled latency and with guaranteed bandwidth. The IEEE 802.1 Audio Video Bridging Task Group is working on standards to meet these requirements, including 802.1Qat Stream Reservation, and 802.1Qav Queuing and Forwarding for AV Bridges.

In November 2012, AVB was renamed as the “Time-Sensitive Networking Task Group” (TSN) which is an enhancement of AVB, adding specifications to expand the range, functionality and applications of the standard. IEEE also standardized IEEE 1722 – Layer 2 Transport Protocol for Time Sensitive Applications in a Bridged Local Area Network – and IEEE 1733 – Layer 3 Transport Protocol for Time Sensitive Applications in Local Area Networks.
The AVnu Alliance is an industry forum dedicated to the advancement of AV transport through the adoption of IEEE 802.1 AVB and the related IEEE 1722 and 1733 standards. The AVnu alliance is supported by most of the OEM and Tier-1 companies, to define a complete Ethernet-based solution for audio and video in IVNs.

**MAC-PHY Security**

Media Access Control Security (MACSec) is an 802.1AE IEEE industry standard security technology and a popular way to secure all data transmission in Ethernet networks. MACsec provides point-to-point security on Ethernet links between directly connected nodes and is capable of identifying and preventing most security threats, including denial of service, intrusion, man-in-the-middle, masquerading, passive wiretapping, and playback attacks.

Additionally, an Ethernet MACSec root node can be utilized as the security center for all domains in the car including lower-speed CAN, LIN, USB, and others. This can be achieved by using one or more trunking ports from an Ethernet switch to an Ethernet supporting gateway, bridging those legacy networks.

**Power Over Cable**

Power delivery over the same single-pair automotive cable that carries the data is an important feature for automotive networks, especially in the case of cameras and sensors that are mounted all around the vehicle. The IEEE 802.3bu standard, which was ratified in 2016, defines specifications and parameters for adding standardized power to single-pair cabling.

The standard defines a power delivery protocol that supports multiple voltages, and multiple classes of power delivery for each voltage, with assured fault protection and detection capabilities for identifying device signatures, as well as communicating directly with devices to determine accurate and safe power delivery. Total power delivery over the automotive cable ranges from 0.5W all the way up to 50W.

After discussing some of the important features of Ethernet for IVN, it is also important to mention some of the misconceptions about Ethernet and its utilization in car networks.

**Misconceptions about Ethernet in IVN**

**“The Ethernet Stack is Too Complicated”**

In order to benefit from all the advantages of Ethernet described in this white paper, only a simple Layer-2 technology, specified in IEEE 802.1P and 802.1Q standards, Virtual LAN (VLAN) technology is needed, which makes it trivial for Automotive applications. In all modern Ethernet chipsets, this is implemented inside the hardware-based data path engine.
Only minimal firmware for VLAN configurations and link management is needed. No complex TCP/IP stacks are ever needed.

It is also important mentioning that the Ethernet stack is the most widely used and proven in the world. Any other stack generally requires that it be converted, via a gateway, to Ethernet, at least for diagnostic purposes, and often for integration to other networks such as the Internet.

Another point to consider is the actual additional cost of hardware (silicon) required to implement the (low) overhead of Ethernet Layer-2 MAC. While in old semiconductor process nodes, the digital portion of the Ethernet MAC was noticeable (compared to the PHY area), in current processes it is extremely small and negligible in cost. For example, in the process for 28nm, the additional cost for a digital block of 10Gbps MAC (including the encapsulation and memory) is 0.6 cents. Yes that is not a typo - this is an added cost of $0.006.

“Ethernet Latency is Too high for Automotive”

When analyzing the latency of Ethernet in IVN, the first question we need to ask is “what is the required latency limit in IVN?” In presentations that OEMs and Tier-1s have presented in IEEE, the requirement was stated as “1ms over 7 hops”. Seven hops include source and destination, meaning six segments and each segment latency should be up to 166µs on average.

A more aggressive limits for latency stems from the design of the SoC/GPU for the vision analytics. These systems are responsible for sensor fusion, object identification and the decisions of the driving controls (braking, steering, accelerating, etc.), thus the delay (latency) of these systems is the most critical one for autonomous driving. Tier-2 companies state limits on latency range of 40µs to 60µs, from the camera output to the SoC/GPU input. These more aggressive limits are used in the following analysis.

The next question for latency analysis is what is included in the latency definition. More specifically, which system layers should be included in the calculation of the total latency?

Figure 6 shows a typical layer structure for a camera to SoC/GPU interface. Without getting to the definition of each layer, what is important to understand is that the only layer that differentiates Ethernet from other IVN transport technologies is the Link layer, for the following reasons:

1. The Protocol and Adaptation layers are related to the camera interface and are very much the same for any automotive transport technology.

2. For a specific targeted speed (for example 10Gbps), the PHY and cable definition will not be much different between different automotive transport technologies (all need to handle the same cable harness impairments like IL, RL, EMC, etc.), and hence the latency is similar.
The Link layer of Ethernet is called Media Access Control (MAC). More specifically, it is the encapsulation + buffer memory + MAC layer, which in this discussion we will refer to all three as "MAC". Let's use the 10Gbps speed for this analysis. The most important parameter that affects the latency is the packet length – the longer the packet the higher the latency.

Ethernet has the inherent flexibility to work with packets with lengths of 64 up to 1,522 bytes. For real-time traffic like video, it is common to use relatively longer packets (to reduce the overhead), for example, packets of 512 bytes. Simple simulation shows that for 512 bytes, the latency added by the Ethernet MAC for a video stream is less than 6µs. Even with the longest standard Ethernet packet of 1,500 bytes, the latency added by the MAC is less than 9µs. (Note: this calculation is for video streaming. For non-video stream, which doesn’t require buffering, the latency is much smaller than that).

Based on the latest presentation in IEEE 802.3ch⁴, a typical latency of 10Gbps Automotive PHY layer is in the range of 3µs, which brings the total of MAC+PHY latency to less than 9µs (or worst case less than 12µs). Based on analysis done by OEMs, this is well within the system requirements, and will also meet the SoC/GPU latency limit of 40µs.

“Ethernet Requires a Lot of Software / Memory / CPU Power”

A typical Ethernet VLAN software library is less than 5 Kilobytes of code and 2 Kilobytes of data memory on all microprocessors. It is implemented as a very small, non-stateful software runtime library. In essence, the “Ethernet Stack” is trivial for Automotive applications, and consists only of OSI Layer 2 data handling, implemented in chip hardware. The CPU utilization of running this library is typically less than 1%. One of the other clear advantages of Ethernet is the ability to send sensor and application data using VLANs, as well as the ability to utilize Ethernet and VLANs for transparent memory to memory transfers between nodes or hosts.

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Based on analysis done by OEMs, Ethernet latency is well within the system requirements, and will also meet the SoC/GPU latency limit.
This can be done with another popular Data Center technique - Remote Direct Memory Access (RDMA), which utilizes the same software library. RDMA is a direct memory access from the memory of one computer into that of another without involving either one’s operating system. RDMA supports zero-copy networking by enabling the Ethernet chip to transfer data directly to or from application memory, eliminating the need to copy data between application memory and the data buffers in the operating system.

Such transfers require that no work to be done by CPUs, caches, or context switches, and transfers continue in parallel with other system operations. When an application performs an RDMA read or write request, the application data is delivered directly to the network, reducing latency and enabling fast message transfer.

### Why Ethernet Has Always Won

Ethernet is by far the most widely used local area networking (LAN) technology in the world today, with billions of ports shipped every year.

The roots of the Ethernet technology began in 1973, when Bob Metcalfe, a researcher at Xerox Research Center (who later founded 3Com), wrote a memo titled “Alto Ethernet”, which described how to connect computers over short-distance copper cable. With the explosion of PC-based Local Area Networks (LAN) in businesses and corporations in the 1980s, the growth of client/server LAN architectures continued, and Ethernet started to become the connectivity of choice for these networks. However, the biggest advancement in Ethernet that made it the most successful networking technology ever, was when its standardization efforts began under the IEEE 802.3 group.

Over the last four decades, many other technologies and protocols have tried to displace Ethernet. ISDN, ATM, Frame Relay, AppleTalk, Token Ring, InfiniBand, just to name a few. Some started as complementary technologies for other networks, and some sought to become a direct solution for LAN. Each technology usually had a single, specific advantage over Ethernet such as smaller latency, higher speed, lower power, or a simplified architecture. Those technologies tried to leverage their respective advantages to propose a complete networking solution that would eventually replace Ethernet. Despite these efforts, they all failed to be deployed in large volume. There are many explanations why Ethernet became the de facto technology for almost every network, but most likely the strongest reasons are the "momentum" and the "snowball effect".

The momentum is related to the way Ethernet is being developed. Under the IEEE 802.3 umbrella, the top networking experts in the world, representing the best networking companies, are meeting every two months, with the goal of innovating, improving, and adding to the Ethernet standard.
With all these great minds in the same room, each one brings their own experience about how a network should work and what features and attributes are required to improve its speed, performance, efficiency, security, interoperability, and reliability. Competing network development efforts have simply paled in comparison. This brain trust is at the core of the unstoppable nature of Ethernet.

The resultant ubiquity and continuous growth of Ethernet created another major advantage: the spreading of the technology. With so many customers, vendors, and developers, the ecosystem of Ethernet is enormous. It starts with the IT people in each company that are experts in Ethernet regardless of what other networking technologies they might need to support. It extends further with the high numbers of hardware and software developers around the globe building new platforms and developing innovative solutions based on Ethernet. This ecosystem keeps growing and increases the technology spread, which in return continues boosting the ecosystem – the snowball effect.

**Ethernet in IVN, and Where It’s Going Next**

The decision to move to Ethernet in automotive happened at least ten years ago. The pioneer OEM was BMW that started promoting the idea of 100M single pair Ethernet for IVN in 2008. Many car models today use 100BASE-T1, and some are upgrading to 1000BASE-T1, which is the latest standard for Ethernet PHY in automotive. Automotive Ethernet is not only for high-end cars. The OEM discussions and level of interest in Ethernet networks for IVN indicate that a significant majority of car manufacturers are planning to move to Ethernet for all classes of cars. The same OEM and Tier-1 vendors are also involved in the IEEE Ethernet standard committees that are developing new solutions and features for Automotive Ethernet.

However, while the automotive industry moved quickly towards higher speed links – especially for higher-resolution cameras, sensors and displays – Ethernet technology and standards were lagging and consequently, missing a very critical component: PHYs that support Multi-Gig rates.

As a result, a vacuum was created in this market, and into this vacuum a few proprietary technologies emerged – for example, LVDS based solutions like GMSL and FPD-Link, APIX, HDBASET, and others. These technologies provided a PHY and in some cases transport protocols that were designed to carry signals over automotive cables at Multi-Gig speeds, to fill in the gap that was created by the absence of a higher-speed Automotive Ethernet PHY.

It didn’t take long for automotive OEMs and Tier-1 vendors to realize that none of these proprietary technologies provide all the existing and required features for IVN that Ethernet already offers. They have started pushing the semiconductor industry to develop a Multi-Gigabit Automotive Ethernet PHY.
The first outcome from that push was an introduction of pre-standard Automotive Ethernet PHY products by Aquantia in 2016/2017, that support speeds of 2.5G, 5G and 10Gbps over existing automotive cables. These products have already been adopted by at least three OEMs at the time of the writing of this paper.

In addition, there was a Call-For-Interest (CFI) in IEEE in 2016 for a new study group for Multi-Gigabit Automotive Ethernet PHY, that later became the 802.3ch task force. The drivers and supporters of the CFI were mostly OEMs such as GM, BMW, Audi, Hyundai, Ford, Toyota, Daimler, Volkswagen Group, Jaguar Land Rover, Renault, and Volvo with Tier-1 providers like Bosch, Continental, Delphi, Denso, Harman, Intedis, and Vector Informatic.

The objective of the study group was to develop Ethernet PHY(s) at rates of 2.5Gbps, 5Gbps, and 10Gbps over a single-pair automotive cable. In the use cases that were presented by the OEMs in the study group, the message was very clear: A Multi-Gig Automotive Ethernet PHY is required to support a solution that is Ethernet from end-to-end, meaning that Ethernet will be used not only in the backbone, but also for the interface to the cameras and sensors.

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Daimler (buntz_NGAUTO_01b_0217) presentation, in IEEE SG February 2017, provides an example for such requirements, as shown in Figure 7.

- **(Core) network (distributed computing)**
  10Gbps potentially needed complex (costly) cable probably accepted

- **Sensor network**
  Sensor needs vary from 10M to 10G/5/2.5Gbps for many applications sufficient asymmetric solution to lower power

- **Connectivity (one link)**
  Probably 5/2/5Gbps symmetric are sufficient

Proposal: adopt objective to allow for further speed grades below 10Gbps and as well asymmetric cata rate solutions (or automatic uni-directional EEE?)

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Figure 7: Use Cases and Speed Grades
The 802.3ch task force is moving nicely towards reaching a first set of Multi-Gig PHY specifications (Draft 1.0) by the end of 2018, and it should be finalized by 2019, with products in the market soon after.

IEEE 802.3cg is another standard for 10Mbps automotive PHY, that is aiming to provide a solution for low-bandwidth network requirements in the car. This standard is now moving to its final stage in the working group ballot.

Since all the other layers and features of Multi-Gig Ethernet already exist –such as MACs that support 2.5Gbps/5Gbps, and 10Gbps, switching, synchronization, QoS, security, and more – it is expected that with the introduction of Multi-Gig PHY products, Ethernet will become the technology of choice for Automotive and replace the interim technologies that filled the temporary vacuum.

This transition will not happen overnight, but with the existing standard Ethernet PHY solutions (100BASE-T1 and 1000BASE-T1), and the introduction of Multi-Gig PHY products from multiple vendors, adoption is expected to continue to increase. The reason for the increased adoption is not only the high speeds and the long list of features. For many OEMs, the huge ecosystem and its ubiquity is one of Ethernet’s biggest advantages.

**Ethernet Ecosystem**

Ethernet has the highest number of semiconductor vendors by far, compared to any other networking market. With standardized specifications via the IEEE and numerous interoperability test houses (like UNH) and Plugfest events, multiple sources are available for many Ethernet products such as PHYs, controllers, switches, bridges, and gateways to other protocols.

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**Figure 8: The Power of the Ethernet Ecosystem**

- Multiple vendors
- Lower cost
- Knowledge / Know-how
- SW/Driver availability from many vendors/sources
- Tools for development and diagnostic
- Wide availability of Bridges from other protocols to Ethernet (e.g. USB, PCIe, CAN, …)
- Dominant network – Eliminates need for gateways to/from specialized networks
Plurality of vendors and economy of scale also ensure that Ethernet can deliver a low-cost network. Other advantages of the widespread ecosystem include:

- The proliferation of knowledge – any company that is involved in the design of networks has people that are familiar with Ethernet, starting from IT people, network architects, SW developers, and installers. The know-how is often there already.

- Development of new features and optimized software stacks for almost any networking application is courtesy of a long list of companies supporting software and driver development.

- The broad availability of tools for development, testing and diagnostic of Ethernet networks from many vendors.

- In addition, bridges from almost any other protocol in the world (USB, PCIe, CAN, DisplayPort, HDMI, MIPI, and many others) to Ethernet, are readily available.

And finally, Ethernet has standards to support all type of mediums including copper, fiber optics, and wireless with these adaptors/routers being available from multiple vendors.

Summary

Ethernet’s presence in IVN has grown dramatically over the last few years and is expected to be over 600M ports by 2023\(^a\). The high number of providers drives the ever-decreasing cost of the hardware needed to support it. Ethernet technology already includes features such as switching, security, QoS, synchronous, power-over-cable, multiple topologies, and more that are required for next generation networks in autonomous vehicles.

Just as important is its ubiquity: the spread of the knowledge, the vast ecosystem of suppliers – including semiconductor, system and software vendor – and the growth of tools, bridges and Ethernet based solutions. All these factors make Ethernet the most highly-featured, low-cost network solution, which are the key advantages for the automotive world.
Author Biographies

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Amir Bar-Niv is a seasoned executive with over 25 years of engineering and marketing experience in the Communication, Consumer, and Automotive semiconductors industries. Mr. Bar-Niv served as SVP and GM of the Video and Consumer group at TranSwitch Corporation. Prior to TranSwitch, Mr. Bar-Niv was a co-founder of Mysticom, a provider of Multi-Gig Ethernet PHY products. Before joining Aquantia, Mr. Bar-Niv led the Marketing and business development of Cadence’s IP group, setting the roadmaps for the Infrastructure and Automotive markets. Mr. Bar-Niv received a BSEE degree from Tel Aviv University and MBA from the University of Phoenix. He is the author of fourteen patents.

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Simon Edelhaus has been working on various networking technologies for the last 25 years and holds multiple patents in the field. He started his career in Tel-Aviv University working on Autonomous Ground Vehicles. His dream is to have a fully autonomous car, so he can finally watch Netflix while getting to work.

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