



# Dissecting the Truth About Automotive PHYs

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## Introduction

In the decades since Henry Ford introduced the Model T and revolutionized the automotive industry, car manufacturers and their suppliers have continued to push the technological boundaries, striving to launch safer vehicles with ever-more features, functionality and comforts.

At no time has this been truer than the present. Progress being made towards autonomous vehicles – where the car will drive us, and not the other way around – is bringing with it a revolution in the technologies being developed and deployed. LiDAR, radar and V2X are just some of the buzzwords being bandied about in corporate offices and tradeshow. But it is not just self-driving cars that are responsible for this revolution – even in today's vehicles, the increasing number of electronics control units (ECUs) is pushing us to the limits of what can be achieved with existing connectivity solutions, and that is before you throw in multiple high-resolution displays, cameras and more.

With the increased number of devices and ECUs in the vehicle, there must be considerable changes in how these elements are connected. Multi-Gigabit connections will be needed to form the backbones and high-speed data links for in-vehicle connectivity architectures. However, given the harsh automotive environment, there is much debate in the industry over how all of this can best be achieved.

## What are the emerging requirements for an automotive data link?

In-vehicle connectivity is evolving to keep up with the advances of in-vehicle technologies. However, the increasing complexities of today's vehicle architectures are introducing new requirements for those data links.

- ▶ **The need for more bandwidth:** Automotive data links are not something new – the CAN bus, for example, one of the most widely-used connectivity solutions, has been around since the 1980's. CAN bus has a maximum theoretical bandwidth of just 1Mb/s, while the newer CAN FD tops out at 12Mb/s. While CAN may be a valid solution for low speed links, it does not come close to supporting the multi-Gigabit speeds that are now required for modern vehicle designs. This ramp-up in data bandwidth derives from new sensors being deployed, the increasing amount of data that flows into and out of the car, the abundance of digital displays being fitted to the passenger cabin and the addition of electronic control functions for new vehicle features. While standardization activities across the automotive ecosystem are in advanced stages of development for the 10-16G range, there will be a clear requirement for much higher bandwidth – even reaching the 100G mark as we move towards autonomous vehicles (see Figure 1.)

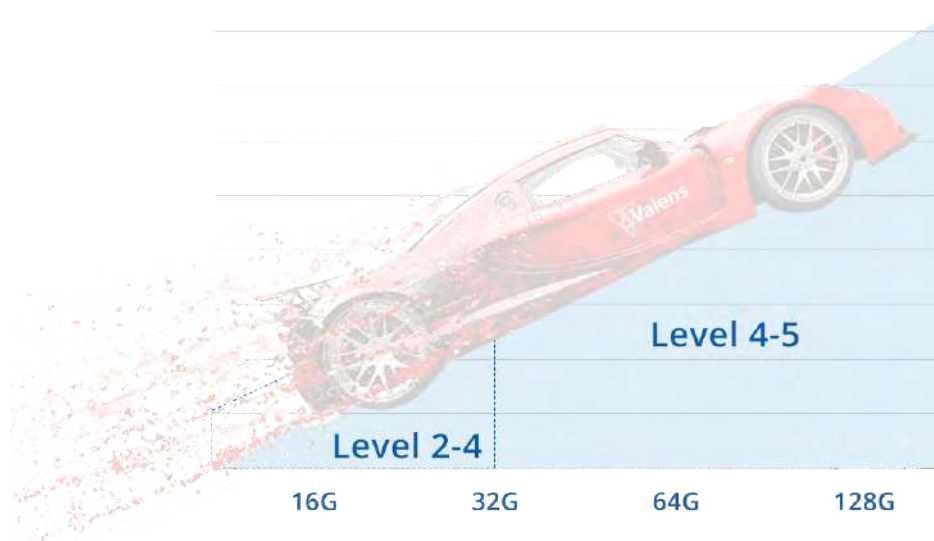


Figure 1: Valens Automotive Bandwidth Roadmap for the Autonomous Vehicle

- ▶ **The need for low-latency:** Mission critical data must be delivered in real time, since any delays in receiving that data could have far-reaching and tragic consequences. It is essential that the delays across the data link be minimized to mitigate the potential risks that latency introduces.
- ▶ **The need for highly robust links over simple wires:** As our cars begin taking control over many of the driver's tasks, the reliability of in-vehicle communications becomes a safety-critical matter. Data must be delivered without failure, even under the harsh electromagnetic interference environment in vehicles.
- ▶ **The need for flexible technologies that cover multiple use-cases:** There are many options available today for in-vehicle connectivity. Different use cases are relying on different data link technologies, simply because there has been no "one size fits all" solution. CAN and LIN, for example, suit applications requiring low bandwidth, and will probably be deployed for many years to come. However, to reduce the number of different connectivity solutions within the vehicle – which brings with it a reduction in cost and complexity – we need solutions that can be used across a wide range of applications.

That is quite a shopping list for the ultimate data link. And bringing it to reality requires new approaches to the most fundamental element of the data link – the physical layer interface, or PHY.

## Let's get physical

The OSI model – which defines a generic structure for communication systems – is divided into seven distinct layers (Figure 2). The PHY is Layer 1 and is responsible for the transmission and reception of raw bit streams over the physical medium. The layers above it each have their own roles and responsibilities in ensuring that the data carried across the link reaches its destination in a way that enables successful communications to be performed.

Host Layers	7	Application
	6	Presentation
	5	Session
	4	Transport
Media Layers	3	Network
	2	Data Link
	1	Physical

Figure 2: OSI 7-layer Model <sup>1</sup>

Different technologies employ different types of PHY, depending upon a multitude of factors including the physical medium used, link speeds and clock frequency. There are a wide range of available PHYs, but for the purposes of this paper we shall focus on two possible PHY signal modulations available for multi-Gigabit automotive links: PAM-4 and PAM-16.

A few words about PAM in general. Pulse-Amplitude Modulation (PAM) is an analog pulse modulation scheme where the message information being transferred is encoded in the amplitude of the signal pulses themselves. The number of possible amplitudes (levels) directly affects the number of data bits that each amplitude conveys, as illustrated in Figure 3.

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<sup>1</sup> ISO/IEC 1989, Information processing systems - Open Systems Interconnection - Basic Reference Model - Part 4: Management framework, ISO/IEC 7498-4 : 1989(E), ISO/IEC, Geneva

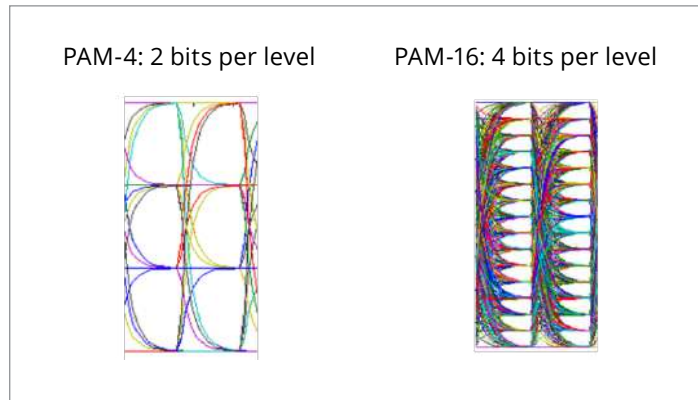


Figure 3: PAM-4 and PAM-16 Eye Diagrams

What this means is that, for any specific symbol rate, a higher number of PAM levels will result in a higher data bandwidth being transmitted over the same channel at a given frequency.

## Channel considerations

It is important to understand the impact that the wiring channel has on the performance of the different PHYs. The symbol rates and Nyquist frequencies for different PAM schemes running at a PHY rate of 12Gb/s is shown in Table 1.

	Bits per Sample	Symbol Rate	Nyquist Frequency
PAM-2 (NRZ)	1	12Gsymbols/s	6GHz
PAM-4	2	6Gsymbols/s	3GHz
PAM-8	3	4Gsymbols/s	2GHz
PAM-16	4	3Gsymbols/s	1.5GHz

Table 1: 12Gb/s PAM Characteristics

Figure 4 shows the insertion loss of a worst-case channel (including wires, connectors and PCB traces), referencing the Nyquist frequency for PAM-2 (NRZ), PAM-4 and PAM-16 PHYs operating at 12Gb/s.

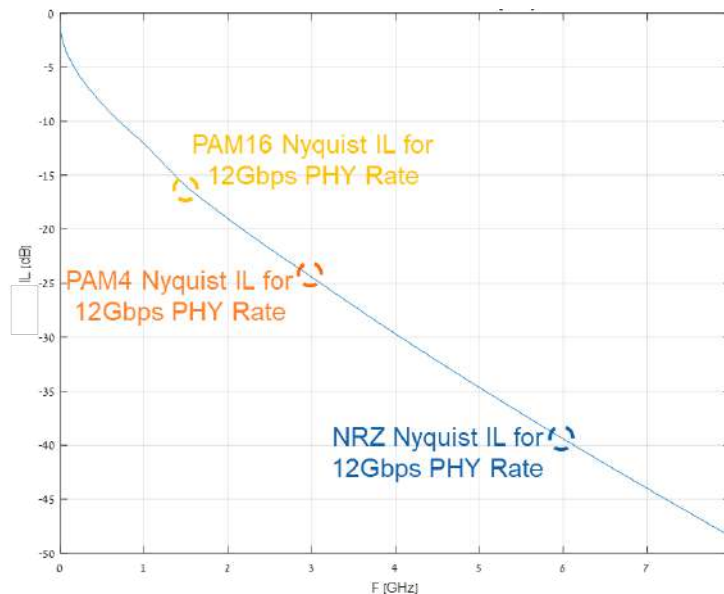


Figure 4: Example Channel Insertion Loss Versus Nyquist Frequency

In Figure 5, we can see insertion loss curves of each PAM scheme, based on the same example channel but normalized to reflect the loss versus the raw bit rate.

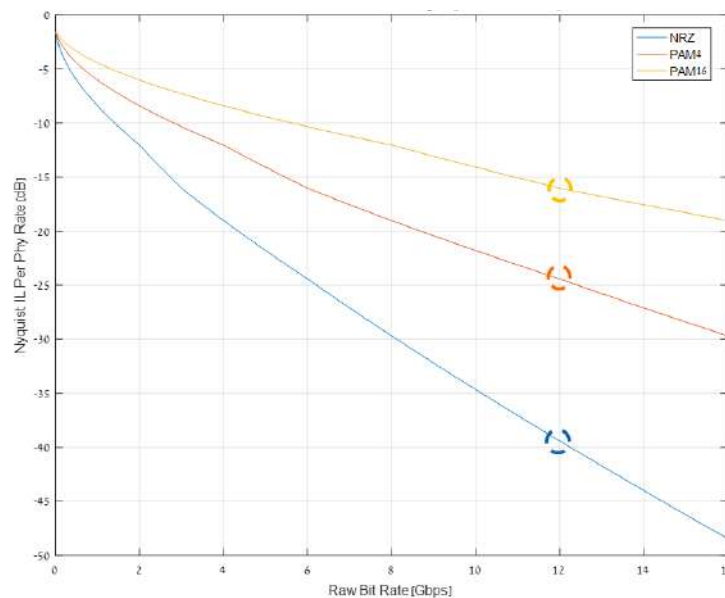


Figure 5: Normalized Insertion Loss Versus Bit Rate

What is clearly shown in both graphs is that as the number of PAM levels increases, the insertion loss is lower irrespective of the data rate that we wish to transmit due to the lower working frequency of PAM-16 versus PAM-4.

## The noisy automotive environment

The car is one of the harshest electromagnetic environments there is. A multitude of sensitive electronic circuits are fitted in close proximity to many sources of noise. High-voltage ignition systems, electric wiper motors, and even simple turn signals – to name but a few – result in the emission of interferences that can wreak havoc on the systems in the vehicle. If we add to that the noise generated by cellphones, communication radios, high-voltage power lines and even from nearby vehicles, the noise levels get even worse. And if that is not enough, cars are always on the move at varying speeds, with different equipment switched on, and in different places, meaning that the noise environment the in-vehicle systems are exposed to is continuously changing and unpredictable. All this noise only adds to the challenges presented by the insertion losses described above.

To be able to reliably work in this complex environment, some form of error correction or noise cancellation is mandatory. Without this, the limitations of the wire channel combined with the levels of noise will degrade the quality of the signal on the wire to the point that the system will not meet the minimum desired bit error rate (BER). The need to overcome the noise is true irrespective of whether the modulation scheme is PAM-4 or PAM-16, but the methods to achieve this are not necessarily the same.

## Forward Error Correction

To ensure the validity of the data being transmitted, PAM-4 PHYs typically make use of Forward Error Correction (FEC). Put simply, a FEC takes the source data and encodes the message in a redundant way using an error-correcting code, which in turn allows the receiver to detect a limited number of errors in the message. Consequently, the system does not need to go out of its way to try and prevent errors from occurring since those errors can be overcome in the receiver, and thus the noises are taken out of the equation.

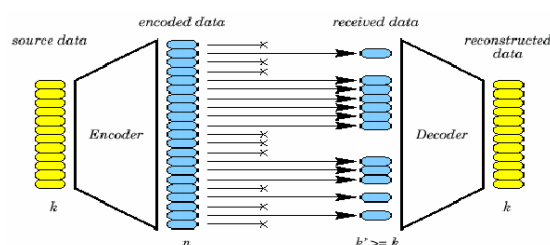


Figure 6: Representation of a FEC Mechanism<sup>2</sup>

<sup>2</sup> Shams, Rifat & Kabir, Md. Hasnat & Ullah, Shaikh 2012, Effect of Interleaved FEC Code on Wavelet Based MC-CDMA System with Alamouti STBC in Different Modulation Schemes. 10.5121/ijcseit.2012.2103.

However, the addition of the redundant data bits adds overhead to the link and thus reduces the effective bandwidth, something that needs to be considered when budgeting the system throughput. As shown in Table 1, since PAM-4 encodes only two bits of data per level, to achieve multi-Gigabit bandwidth we need a very high symbol rate (6Gsymbols/s for a 12Gb/s data rate). This, in turn, imposes a higher clock speed on the system and means that a PAM-4 PHY is subject to high insertion losses in the wire.

## FEC limitations

Unfortunately, FEC-based solutions are restricted in the noise profiles that they can overcome. The limited number of taps in the FEC means that it can only respond to gradual noise profiles—for example, correcting a random bit error caused by poor link quality. Where the FEC proves ineffective is in its ability to cancel harsh instantaneous noise profiles such as those deriving from an electromagnetic compatibility/interference (EMC/EMI) event, which are inherent in the automotive environment. Conventional noise cancelling techniques – even if added after the FEC– are not sufficient to counter such instant noise attacks, and we shall shortly discuss another approach that is needed.

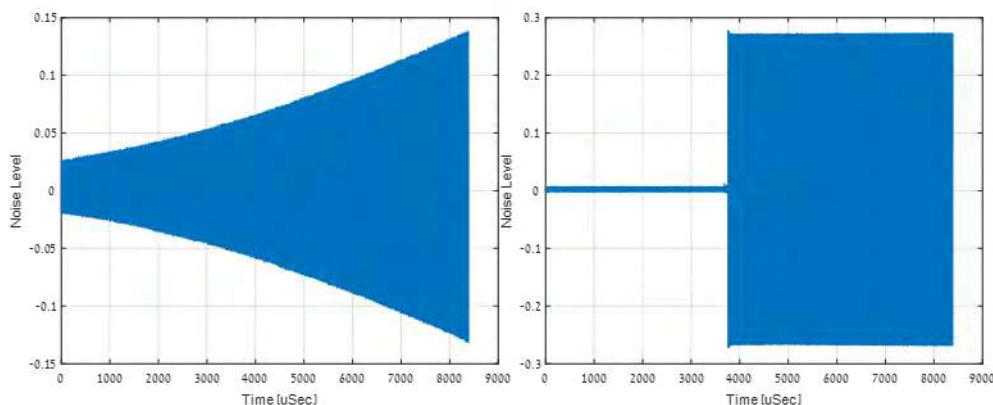


Figure 7: Gradual Versus Instant Noise Profiles

It is also necessary to understand how much the FEC can improve the receiver decision separation budget for the PAM levels. The decision point is the amplitude level at which the receiver decides whether the data sample belongs to the PAM level above or below the sampled data point. This is illustrated in Figure 8. The higher number of PAM levels leads to a smaller amplitude difference between each level which, in turn, reduces the distance between the decision points.



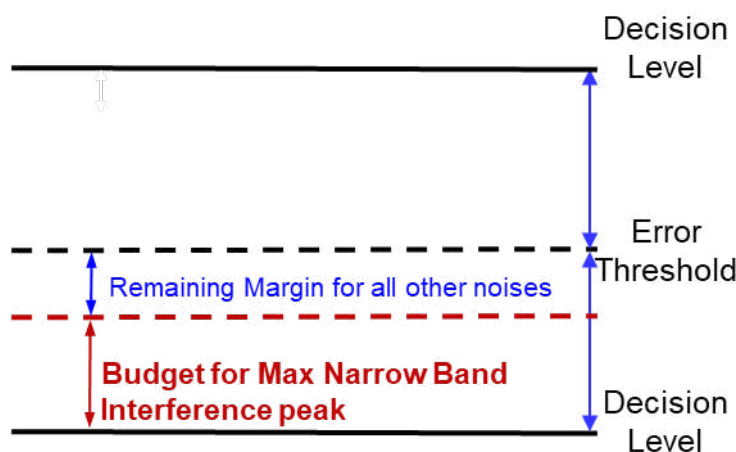


Figure 8: Decision Levels and Noise

When we consider PAM-4 with its FEC, the error correction ability can tolerate a larger budget which can be assumed to be 70% of Separation Distance/2 (the “error threshold”), equivalent to -3dB. However, this does not provide enough margin for a PAM-16 modulation.

One final point to consider is that the FEC is always active, irrespective of the noise levels in the system. This not only results in reduced bandwidth at all times (due to the overhead of the extra bits), but is also wasteful in terms of power consumption in the silicon.

## Fast noise cancellation and local retransmission

Unlike the usage of FEC to correct errors after they occur, it is possible to adopt a “prevention is better than cure” approach to reduce the likelihood of errors being generated. This is achieved through the use of fast adaptive noise cancellation, which can be automatically activated only when needed (“just in time cancellation” or JITC). The JITC neutralizes the effects of external noises on the system, removing the threat before it reaches the receiver. Even when considering the lower signal-to-noise ratio with PAM-16 (due to the proximity of the signal amplitudes), the noise cancellation provides a greatly reduced noise floor at the source compared to PAM-4 and its associated FEC. However, this is still not enough to entirely overcome the effects of an instant noise attack, and for this an additional and highly-effective technique can be employed: local retransmission.

Should a data error be detected in the receiver, a retransmission request is sent back to the transmitter. The data packet is then resent using a lower PAM modulation (see Figure 9) – for example, if the original packet was transmitted using PAM-16, the retransmitted packet is sent using PAM-8 (“subset modulation”). This enlarged separation between the PAM-8 levels greatly enhances the signal-to-noise ration of the retransmitted data, which effectively reduces to zero the likelihood of the packet being received again with an error. Meanwhile, all other packets that are error free continue to be transmitted utilizing PAM-16 modulation. What is unique about this retransmission mechanism is that it all occurs at the PHY layer without any intervention from higher layers. Consequently, the delay introduced by the retransmission is so close to zero that it has no effect on the overall link latency.

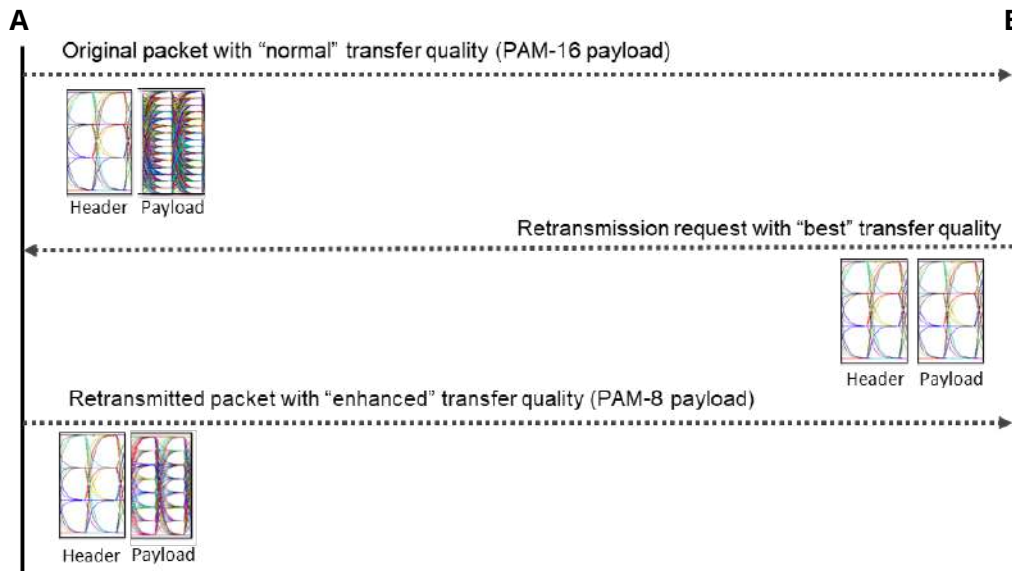


Figure 9: Local Retransmission with PAM-Subset Modulation

It is this winning combination of fast noise cancellation and local retransmission that is implemented in the Valens PAM-16 automotive PHY to ensure the link operates error-free at the optimal operating point. As a result of this approach, the Valens solution is a zero packet-loss technology, with every packet delivered for maximum data integrity.

## Decision separation comparison – PAM-16 versus PAM-4

Making a calculation of decision separation for the PAM-16 solution with its noise cancellation and retransmission mechanisms, it can be shown to tolerate peak noise greater than 30dB over the error threshold – this is 3000% of Separation Distance/2, equivalent to +30dB.

Figure 10 shows the Decision Separation losses for PAM-4 and PAM-16, without taking into account external noises. However, once we factor in the external noise and the effects of the FEC and noise cancellations and retransmission, we see that the PAM-16 normalized insertion loss curve greatly outperforms the PAM-4 normalized curve (Figure 11), with consistently lower losses at all bit rates.

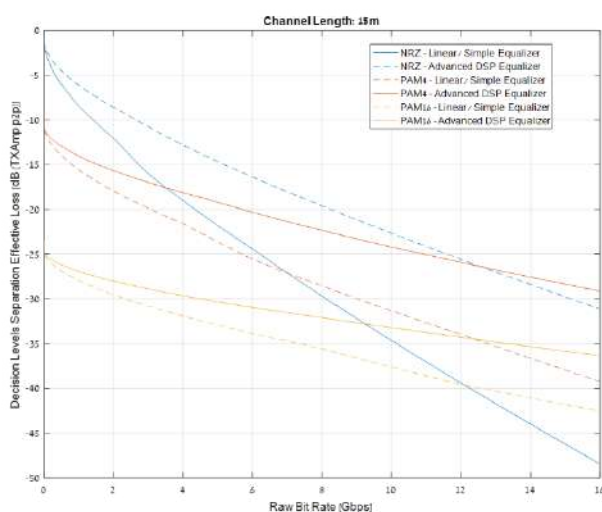


Figure 10: Decision Level Separation Versus Bit Rate

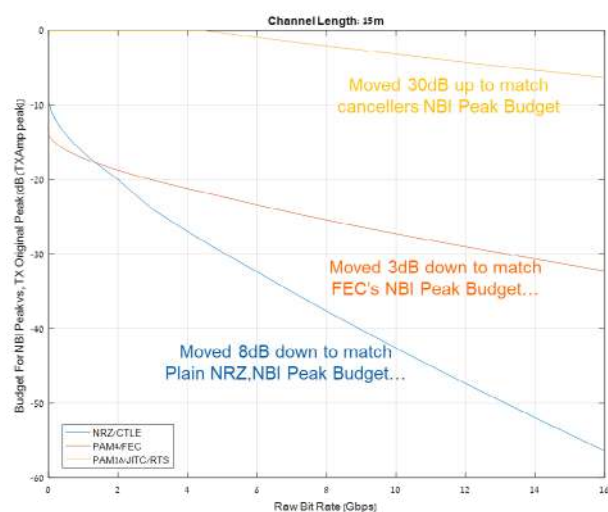


Figure 11: Effect of PAM-4 FEC and PAM-16 Noise Canceller + Retransmission

## The question of power

Of course, there may be concerns that implementing a PAM-16 solution is more complex and more expensive. Actually, the opposite is true. PAM-16 consumes less power – and occupies less silicon area – when compared to a PAM-4 alternative. This is the result of PAM-16 using a lower symbol rate (i.e. lower clock frequency) when compared to PAM-4 for any given data rate. This lower speed allows for the PAM-16 solution to utilize slower, smaller and less power-consuming gates in the silicon, resulting in an overall smaller area and power consumption compared to a PAM-4 solution at the same data rate.

## Beyond the PHY

It is also important to consider the impact of the other layers in the OSI model when assessing the overall complexity of PAM-4 and PAM-16 communication channels. For this, we shall look at how those upper layers are mapped for an Automotive Ethernet implementation and the Valens Automotive solution.

The Automotive Ethernet protocol stack is very well defined with clear layer separation. However, as Ethernet was not designed for time-sensitive applications (TSN), the upper layers are full of software implementations to meet the new TSN requirements. This software, while providing flexibility, adds complexity to the implementation of in-vehicle Ethernet networks as well as adding latency to the data path.

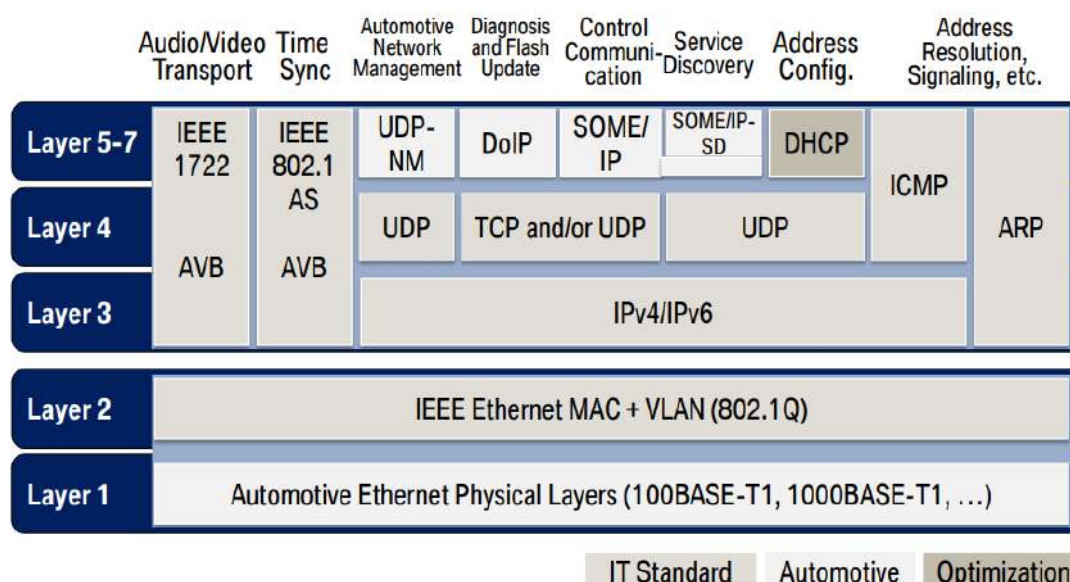


Figure 12: Automotive Ethernet Protocol Stack<sup>3</sup>

<sup>3</sup> Matheus, Dr. Kirsten 2018, Evolution of Ethernet-based Automotive Networks: Faster and Cheaper, Proceedings of 8th Ethernet & IP @ Automotive Technology Day, viewed 4 March 2019, <[https://standards.ieee.org/content/dam/ieee-standards/standards/web/documents/other/d1-03\\_matheus\\_evolution\\_of\\_ethernet\\_based\\_automotive\\_networks.pdf](https://standards.ieee.org/content/dam/ieee-standards/standards/web/documents/other/d1-03_matheus_evolution_of_ethernet_based_automotive_networks.pdf)>

The Valens Automotive protocol stack, by comparison, is hardware-based all the way up to the Application layer (Layer 7). This optimization leads to link latencies of only a few microseconds and minimizes the software development effort required for the deployment of such links.

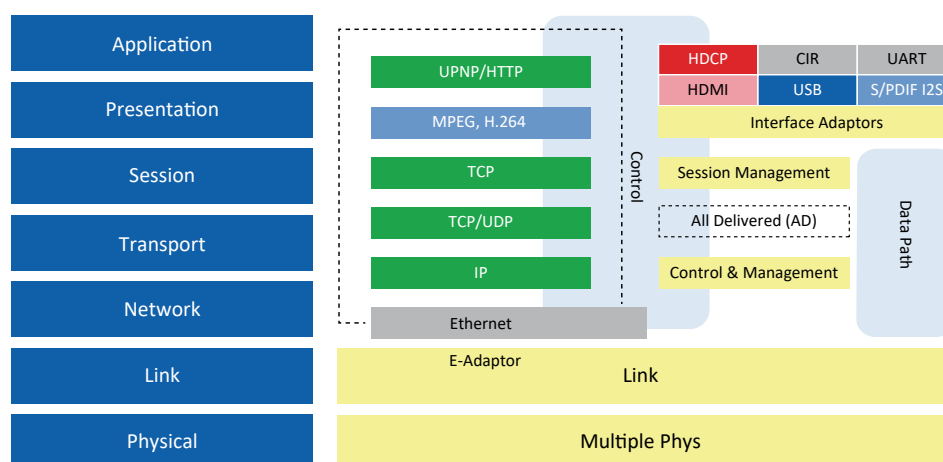


Figure 13: Valens Automotive Communication Stack

Valens' implementation of a PAM-16 data link brings with it a number of additional benefits:

- ▶ Through its unique dynamic subset modulation, different data types can be encoded using different PAM levels, and not only PAM-16. For example, non-critical data requiring high bandwidth (such as video streaming at 4K resolutions) can be coded using PAM-16 since even if data errors occur, the effect will not be noticeable. However, for mission-critical data – including that for sensors and actuators – or if running across a deteriorated link, the data can be encoded at PAM-8 or even PAM-4, which greatly increases the noise margins to further reduce the bit-error rate (BER) and thus the likelihood of errors being received.
- ▶ A secondary benefit of the subset modulation is that the Valens solution is an “all delivered” communication channel with zero packet loss. Since BER can be controlled using different PAM encodings, and with the benefit of local retransmission, every data packet received is accepted and no packets are dropped.
- ▶ Valens' technology enables the convergence of different interfaces – audio, video, USB, PCIe, controls and even multi-Gigabit Ethernet. With its adaptive noise cancellation and local retransmission mechanisms, Valens technology can transmit today up to 2.5G Ethernet on a single wire.

## Conclusion

The need for faster in-vehicle data links is upon us. The plethora of bandwidth-hungry applications being rolled out in today's cars means that existing connectivity technologies are simply not up to speed. We have explored two of the latest PHY modulation techniques being deployed (PAM-4 and PAM-16), looked at their limitations and addressed how each of them overcomes the challenges of the automotive environment, including cable losses and noise immunity.

Without doubt, there is room in the automotive industry for more than one in-vehicle multi-Gigabit connectivity solution. However, we have seen that a solution employing PAM-16 with "just in time" fast noise cancellers and highly-efficient local retransmission optimizes the operating point of the system to provide error-free transmission over simple wires. This offers the most robust approach for multi-Gigabit data links, providing the necessary noise margins at the lowest power and area costs, for the ultimate data center on wheels.