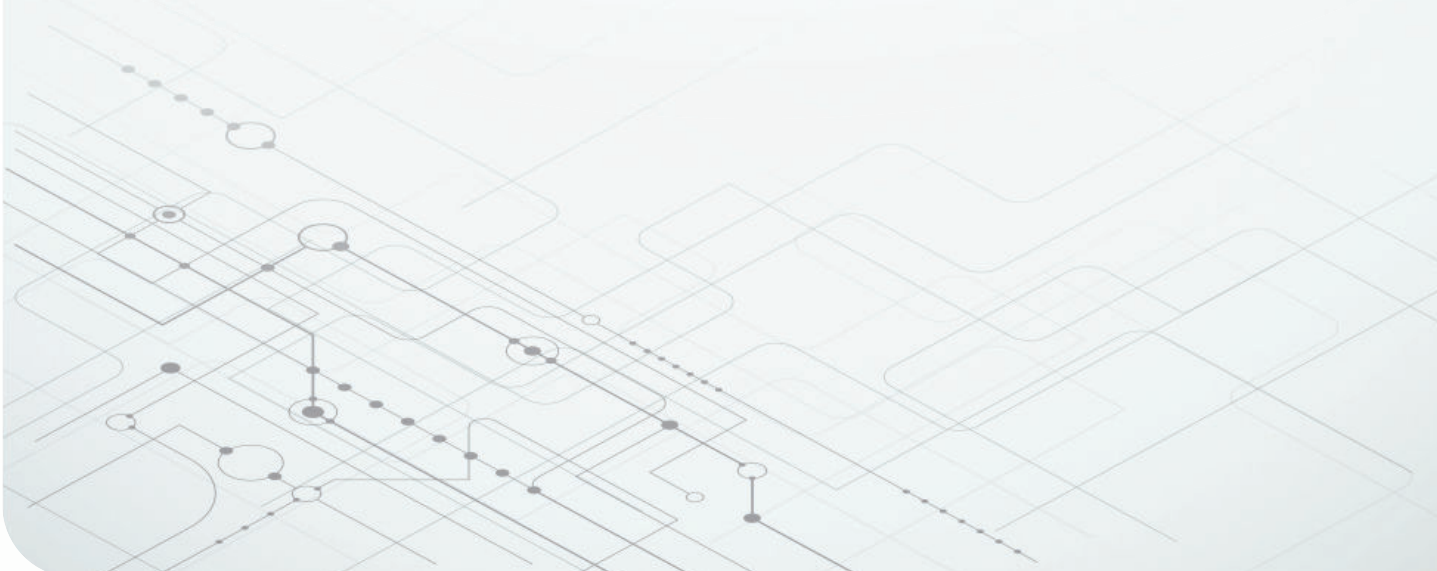


TSN in Automotive Zone Architectures: Enabling Ethernet Ring Architectures and AVB-Distributed Audio



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At a glance



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4

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Introduction

Automakers are pushing to advance high-speed Ethernet backbones in their vehicles with new trends, such as the Ethernet ring architecture for redundancy and Time-Sensitive Networking (TSN) and Audio Video Bridging (AVB) to deliver time-sensitive data reliably.

The industry needs higher bandwidth and faster communication networks to transmit safety-critical and time-sensitive data throughout their vehicles. In next-generation zone architectures, they are investigating Ethernet ring architectures for redundancy while adding more data types to the Ethernet backbone to reduce wiring harnesses, including audio.

Zone architectures leverage zone control modules (ZCMs) to transfer data from various sensors and electronic control units (ECUs) through an edge-node communication network. These ZCMs forward the combined sensor data to the central computing unit (CCU) through backbone communication, as shown in Figure 1.

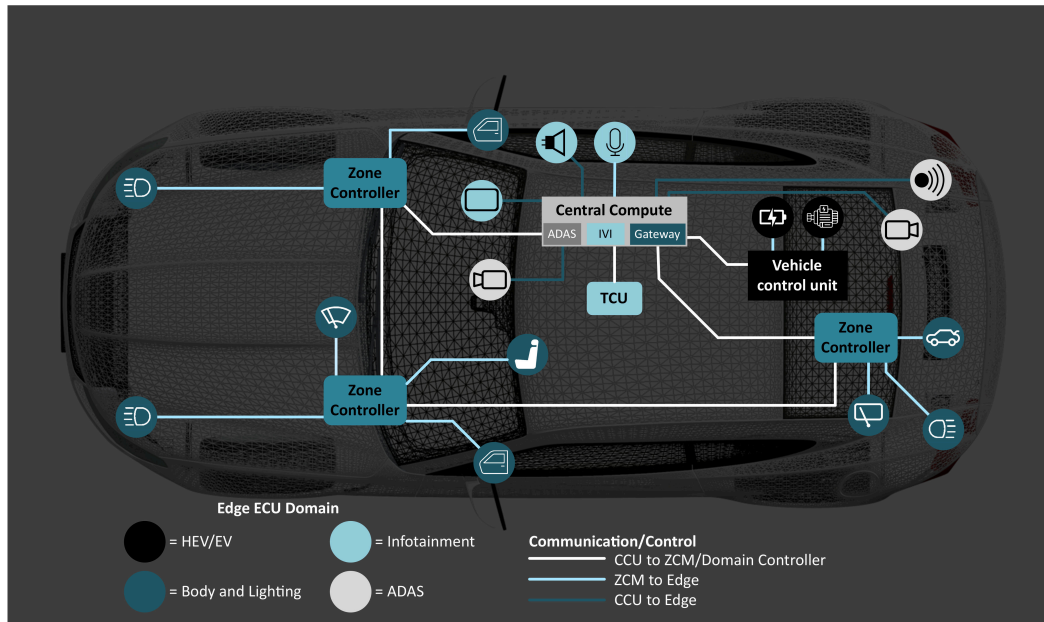


Figure 1. In-vehicle networking for a zone architecture

An Ethernet ring architecture builds on the existing high-bandwidth Ethernet backbone and provides redundancy by connecting each node in the ring to two others. Since the data can travel in both clockwise and counterclockwise directions, the CCU can still communicate with the ZCMs even if an Ethernet link breaks.

Increasing the vehicle network bandwidth enables the transmission of additional data such as audio, radar and camera data over the Ethernet backbone. While automakers are initially bringing primarily body functions into zones as they switch to zone architectures, an ideal zone architecture incorporates cross-domain applications. Audio is a prime target because of AVB standards, which provide deterministic latency for the audio data. Moving audio playback into the ZCM can eliminate the need for a separate communication bus, since it's possible to transmit audio data over Ethernet.

Enabling real-time control and time-sensitive data

TSN ensures the synchronization of time-sensitive data over Ethernet networks. Adding time-sensitive data and enabling real-time control over vehicle networks increases the reliability requirements to maintain high-speed communication links between the CCUs and zones. Because of this, the redundancy support provided by an Ethernet ring architecture is beneficial for TSN applications, including Ethernet AVB; however, a ring architecture is not a requirement for TSN and vice versa.

Several protocols include definitions of TSN:

- Institute for Electrical and Electronics Engineers (IEEE) 802.1AS – Generalized Precision Time Protocol (gPTP) provides data synchronization with deterministic latency, low packet delay variation and low packet loss.
- IEEE 802.1Qbv – Enhancements to traffic scheduling.
- IEEE 802.1Qav – Support for AVB.

While TSN is not required for Ethernet ring architectures, it helps ensure low and deterministic latency. IEEE 802.1AS defines a method for data synchronization with millisecond to nanosecond accuracy. This accuracy level provides benefits to Ethernet ring architectures by applying adjustments and timing compensation to offset latency during the packet processing and transmission process. Additionally, IEEE 802.1Qbv provides support for scheduled traffic enhancements, which helps prioritize and manage Ethernet backbone data.

TSN is necessary for audio data because it ensures synchronized audio playback at different locations in the vehicle, despite varying path delays. IEEE 802.1Qav defines AVB support for sending audio and video data over Ethernet.

Ethernet topologies: Ring vs. star

Many first-generation zone architectures use a star topology, where point-to-point Ethernet connects the CCU to each ZCM. Thus, the communication between each ZCM is through the CCU, or through an additional point-to-point Ethernet connection for direct zone-to-zone communication from the right ZCM to the left ZCM. Alternatively, ring topologies connect every node in a loop, allowing data to travel both clockwise and counterclockwise around the loop. **Figure 2** compares a ring topology to a star topology.

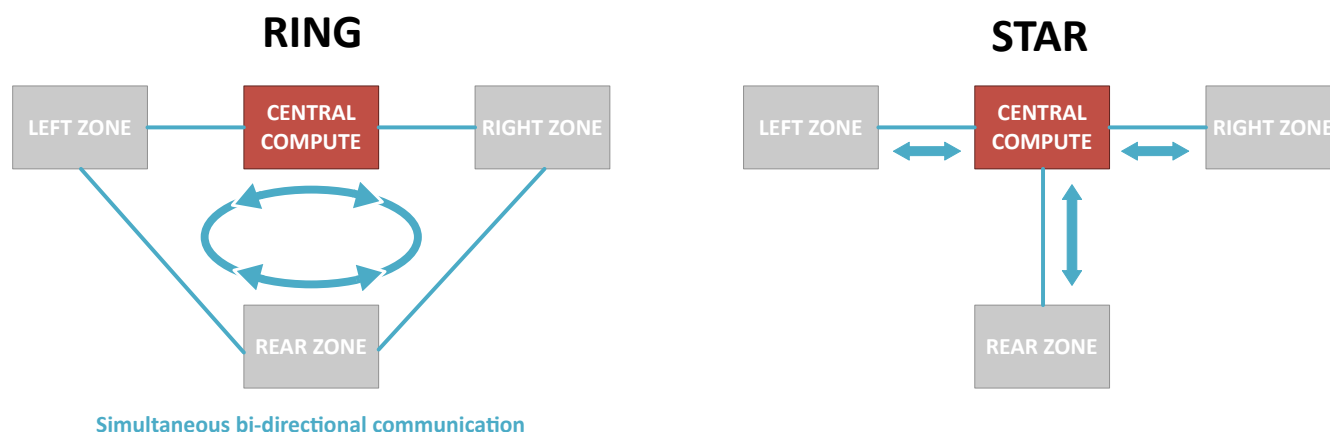


Figure 2. A ring vs. star communication path in normal operation

Figure 3 demonstrates both topologies when an Ethernet link fails. Ring topologies maintain communication to all zones through alternating, unidirectional Ethernet. Additionally, they eliminate switchover time by sending data simultaneously in both directions, so if one path fails, data continues flowing in the other direction without delay, which is vital for safety-critical data transmission from one ECU to another. When an Ethernet connection breaks in a star topology network, all communication with the ZCM stops immediately, forcing it into limp-home mode and defaulting to a predefined safe condition.

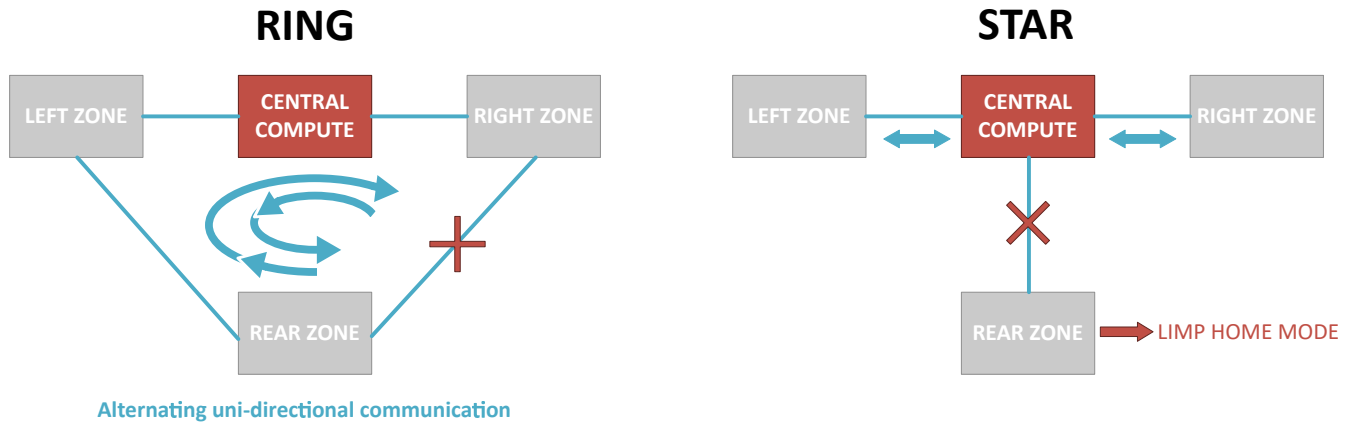


Figure 3. A ring vs. star communication path upon the loss of an Ethernet connection

Ethernet ring architectures offer inherent redundancy, while star architectures require additional communication links to achieve the same protection, as Figure 4 shows. Adding duplicate communication links such as Ethernet or Controller Area Network (CAN) to each ECU increases system cost and weight.

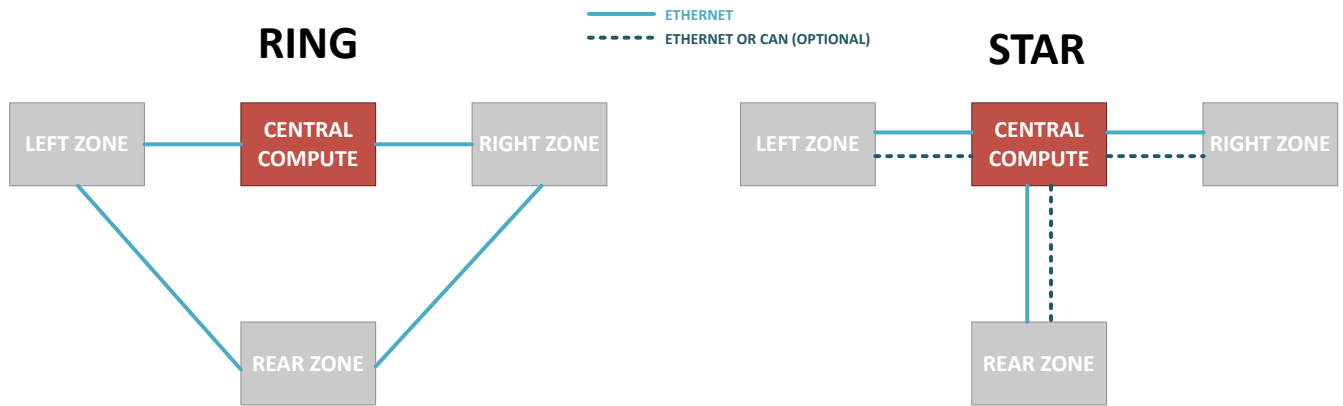
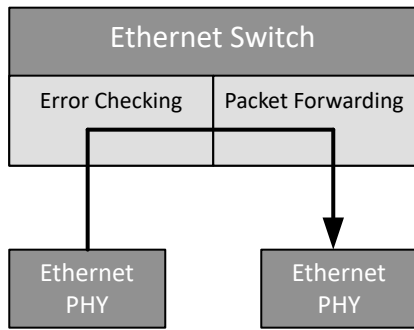


Figure 4. Redundancy in ring vs. star topologies

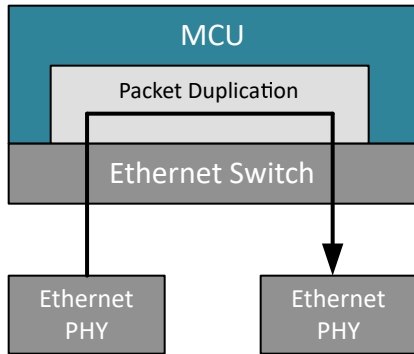
One drawback of an Ethernet ring architecture is the additional latency caused by the increase in the number of nodes between ECUs. For example, an Ethernet ring architecture with four nodes has more end-to-end latency than with three nodes. This added latency comes from packet residual delay in the switch of each ECU and software latency for packet duplication, as Figure 5 illustrates.



A

Packet Residual Delay:

The time it takes for an Ethernet packet to travel through the switch due to error checking and packet forwarding logic



B

SW Latency for Packet Duplication:

The time it takes for an Ethernet packet to be duplicated through software

Figure 5. Packet residual delay and packet duplication in software

Table 1 calculates the added latency.

Packet length	Packet residual delay in switch (A)	Software latency for packet duplication (B)
64 bytes	1.8μs	10μs
256 bytes	3.2μs	10μs
512 bytes	5.2μs	15μs
1,518 bytes	13.2μs	25μs

Table 1. Ethernet ring latency from residual packet delay and packet duplication in software

Table 1 assumes 2,000 packets per second (PPS), 1Gbps Ethernet, and 400MHz CPU operation (one core and less than 60% loaded).

Equation 1 expresses the end-to-end latency for an Ethernet ring architecture as:

$$\text{EndtoEndLatency} = (2A) + (A \cdot \text{No. of nodes}) + B \quad (1)$$

where A is the packet residual delay in the switch and B is the software latency for packet duplication.

Ethernet ring architecture implementation

An Ethernet ring implementation requires a microcontroller (MCU), Ethernet switch and two Ethernet physical layers (PHYs) per node. The MCU encapsulates and decapsulates data, converting other data packets into Ethernet packets and vice versa. Ethernet switches provide hardware offload support for packet forwarding, duplication, ring termination and duplicate packet rejection as defined in IEEE 802.1cb (or through software if hardware support is not available). Three different implementation options exist today, as shown in **Figure 6**.

- An MCU with an external Ethernet switch and external Ethernet PHYs.
- An MCU with an integrated Ethernet switch and external Ethernet PHYs.
- An MCU with an external Ethernet switch that has integrated Ethernet PHYs (it is also possible to use external PHYs in combination with integrated PHYs).

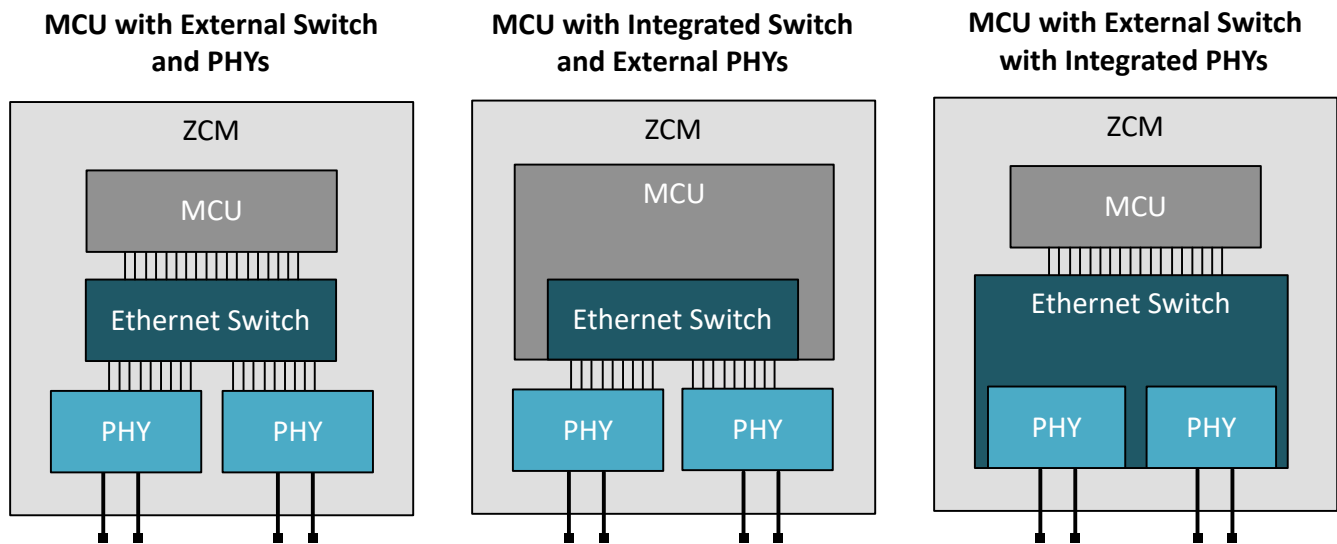


Figure 6. Ethernet ring hardware implementation options

When deciding between the different hardware implementations, consider cost, application and latency. Integrated switches typically cost less than external ones. Zone controllers usually only need five or fewer Ethernet connections to communicate with other high-speed ECUs such as ZCMs, the CCU and radar modules. Most available Ethernet switches include eight or more ports, increasing system costs if only five or fewer ports are required.

Ethernet switches (integrated or external) with dedicated hardware for processing advanced protocols such as IEEE 802.1cb significantly reduce latency compared to software implementations, which add approximately 20µs. Switches with IEEE 802.1Qbv capability further optimize latency by enhancing traffic scheduling through priority queues. TI offers various MCUs supporting Common Platform Switch (CPSW), IEEE 802.1Qbv and functionality similar to what is found in IEEE 802.1cb.

Figure 7 shows an Ethernet ring implementation using a TI MCU (AM263P4-Q1 with an integrated CPSW and external Ethernet PHYs).

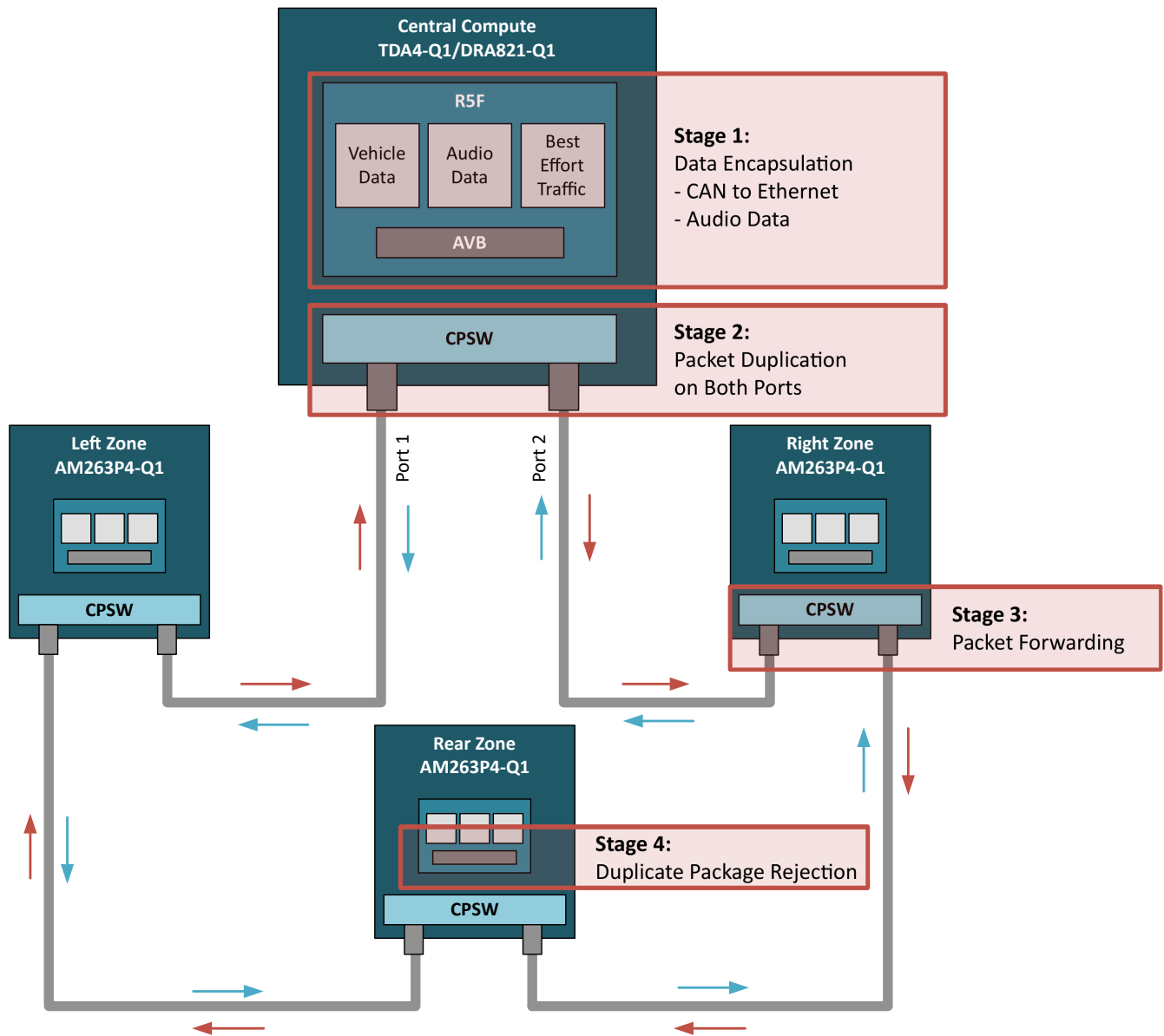


Figure 7. An Ethernet ring implementation using the AM263P4-Q1

The Ethernet ring implementation process starts with data encapsulation within the MCU, as shown in Stage 1. This data can comprise high-priority vehicle data from CAN, Local Interconnect Network, other automotive interfaces, audio data and best-effort traffic. In Stage 2, the system duplicates packets at both Ethernet ports to send data in clockwise and counterclockwise directions, using either software or hardware, depending on the switch capabilities. The AM263P4-Q1 is able to do this through hardware.

During Stage 3, when a node receives data with a destination media access control (MAC) address that does not match the PHY's MAC address, the Ethernet switch forwards the packet to the next node in the ring. In Stage 4, the destination node drops duplicate packets through software or hardware, preventing the ZCM from processing identical packets arriving from both directions. Ring termination also works with duplicate packet rejection to help prevent redundant frames in the ring from circulating endlessly.

TI's AM263P4-Q1 MCUs excel in Ethernet ring applications, since their CPSW implements packet duplication in hardware, reducing end-to-end latency by as much as 69µs for 1Gbps Ethernet. **Table 2** compares latency at each stage based on software vs. hardware packet duplication, assuming 10000 packets per second and a 1500-byte payload.

Stage	Software or hardware	Latency with stage 2 in software		Latency with stage 2 in hardware	
		Average	Maximum	Average	Maximum
Stage 1	Software	23µs	122µs	23µs	122µs
Stage 2	Software or hardware	16µs	79µs	10µs	
Stage 3	Hardware	10µs			
Stage 4	Software	25µs			

Table 2. Latency with packet duplication in software vs. hardware

Adding audio playback to an Ethernet backbone with AVB

Although a ring architecture is not required for AVB, the redundancy it provides enables more data to safely pass through the ZCMs. AVB preceded TSN, focusing specifically on audio applications before expanding into TSN for broader TSN data types. Today, AVB refers to audio-specific TSN applications that distribute audio playback throughout zones by transmitting audio packets over Ethernet. The primary AVB protocols are:

- IEEE 802.1BA – AVB framework for architecture and profiles.
- IEEE 802.1Qav – AVB traffic scheduling for time-sensitive networks.
- IEEE 1722 – the AVB transport protocol.

Audio playback requires delivering audio data at a set sample rate to audio amplifiers. In order to play audio simultaneously in multiple zones, each zone must maintain time alignment to avoid audio fidelity issues related to phase misalignment. AVB enables consistent, time-aligned playback of audio across ZCMs by compensating for varying packet latencies in Ethernet networks.

Audio in zone architectures

Vehicles typically handle four types of audio data:

- Vocal capture through a microphone for hands-free calling.
- Noise capture through road sensors or microphones for active noise cancellation (ANC).
- Audio playback on interior speakers for infotainment and ANC.
- Audio playback for acoustic vehicle alerting system exterior speakers in hybrid and electric vehicles.

Today's typical audio solutions use a separate proprietary audio bus or analog signals to send data throughout the vehicle. Ethernet AVB is a nonproprietary solution that reduces cabling by using the existing Ethernet backbone to send audio playback data from the CCU to the zones. Audio playback on interior speakers is the first type of audio data adopted for use on the Ethernet bus. **Figure 8** shows implementation approaches.

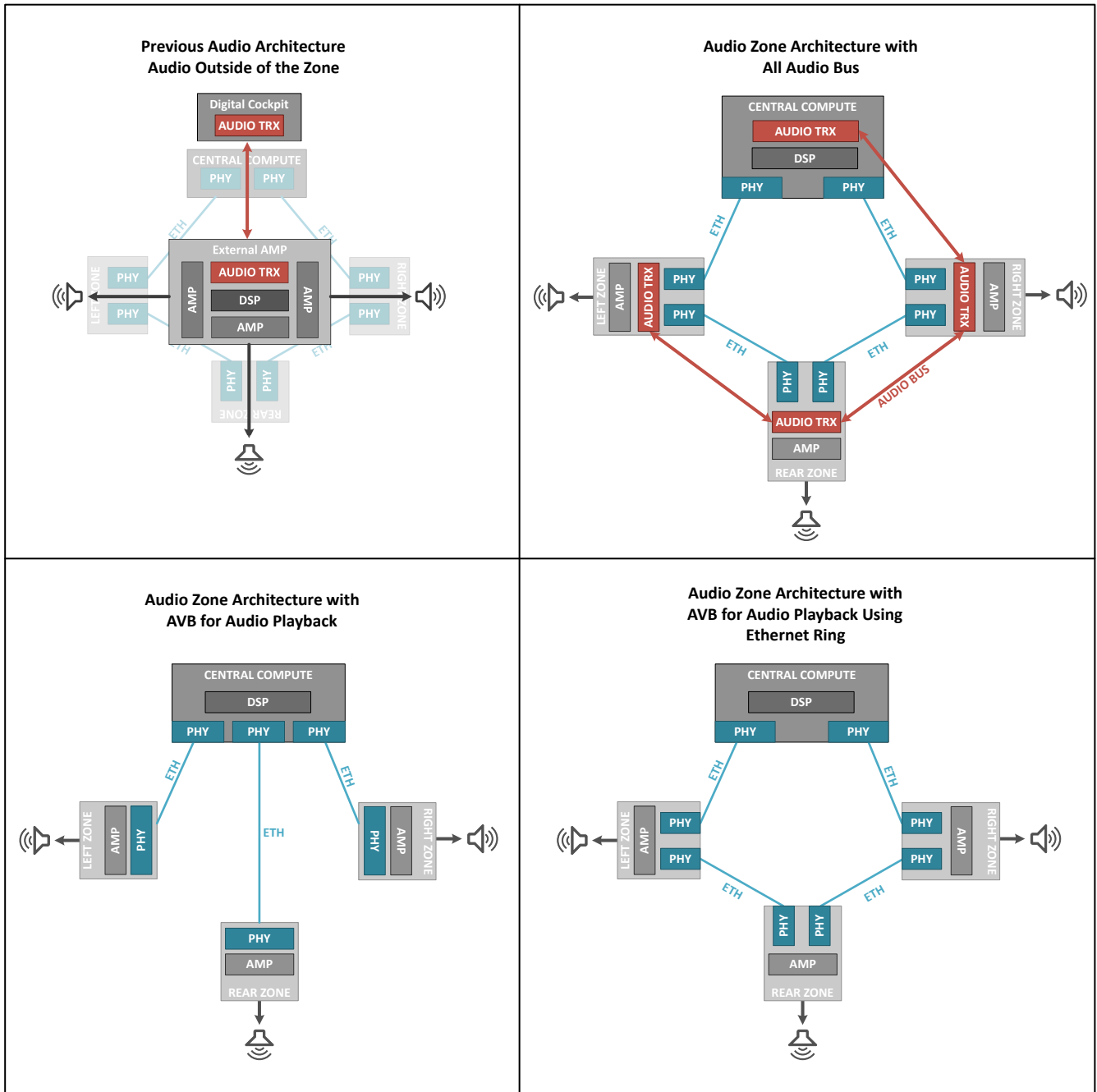


Figure 8. Four potential audio playback solutions

The first example in [Figure 8](#) represents legacy audio bus networks independent of the vehicle architecture. All sound-capture data travels over a digital audio bus; the CCU or digital cockpit ECU handles infotainment audio data, while the external amplifier module manages digital signal processing and speaker output. The main downside of this architecture is the long cabling required from the external amplifier module to the speakers.

The second diagram in [Figure 8](#) demonstrates an audio implementation in a zone architecture using a separate audio bus. Sound-capture data still transmits through the digital audio bus to the CCU for digital signal processing. Audio playback data then moves from the CCU over the digital audio bus to the ZCMs for amplification and output to the

speakers. This approach shortens speaker wiring length because of the location of the audio amplifiers; however, the audio bus becomes much more complex.

The third and fourth diagrams in **Figure 8** show AVB audio playback implementation. Digital signal processing still occurs in the CCU, but audio playback transmits over Ethernet. This works with a star and ring topology; however, a ring topology provides added redundancy for the audio data. This approach also simplifies the audio bus while keeping speaker cabling short.

Implementing AVB in the ZCM

An Ethernet network typically includes an MCU, an Ethernet switch and an Ethernet PHY, often with some integration. These components achieve media clock synchronization (**Figure 9**) through:

- Ethernet MAC.
- Ethernet PHY.
- IEEE802.1AS (gPTP).
- IEEE1722 media clock recovery.
- Media clock generation.

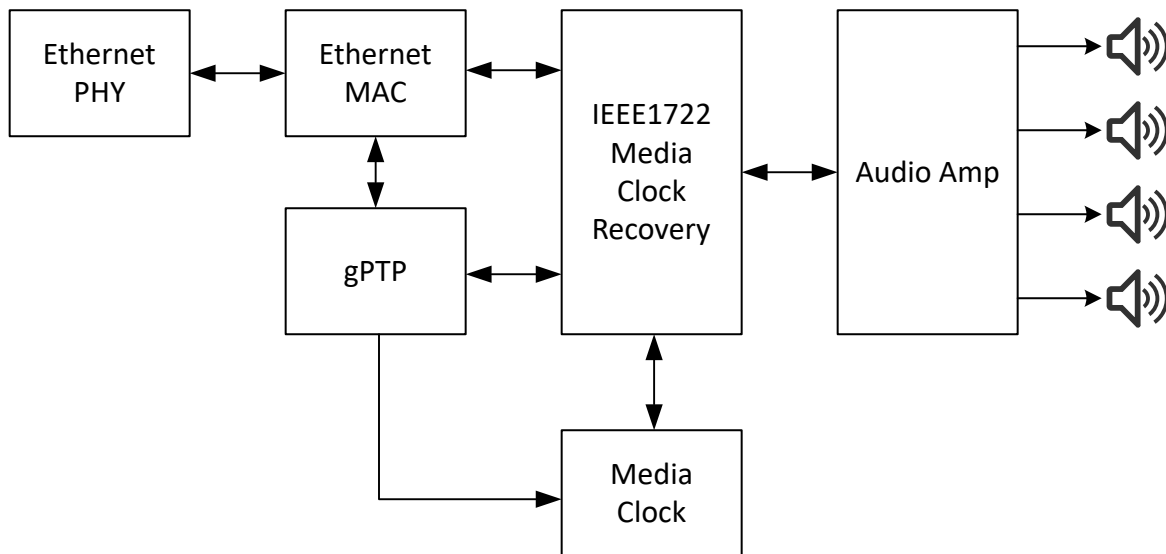


Figure 9. Diagram of media clock synchronization solution

The Ethernet PHY is responsible for transmitting and receiving Ethernet packets. The Ethernet MAC manages data transmission by encapsulating and decapsulating packets. The gPTP protocol synchronizes local clocks across all network devices to maintain a consistent time base. IEEE 1722 media clock recovery uses embedded timing information in Ethernet packets to adjust the audio media clocks: an audio sample clock known as frame synchronization (FSYNC) and an audio data serializer bit clock (SCLK).

Figure 10 shows possible component figurations for an AVB implementation.

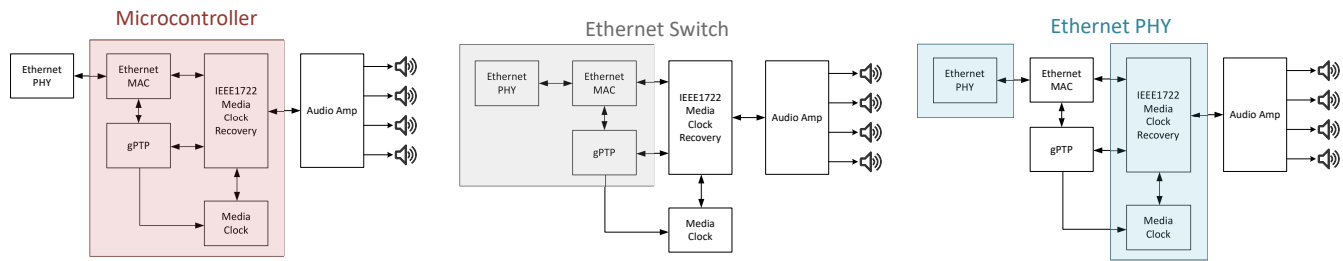


Figure 10. Achieving media clock synchronization in an MCU, Ethernet switch and Ethernet PHY

TI's solution uses the DP83TG721-Q1 with integrated media clock recovery to resynchronize the local media clock based on the incoming Ethernet stream. The PHY generates the media clock (FSYNC) for audio sample rates and the bit clock (SCLK) in hardware. The PHY hardware also manages the audio packet presentation time handling. The AM263P4-Q1 MCU emulates I²S audio data through its programmable real-time unit to communicate with the TAS6754-Q1 audio amplifier. **Figure 11** shows this solution.

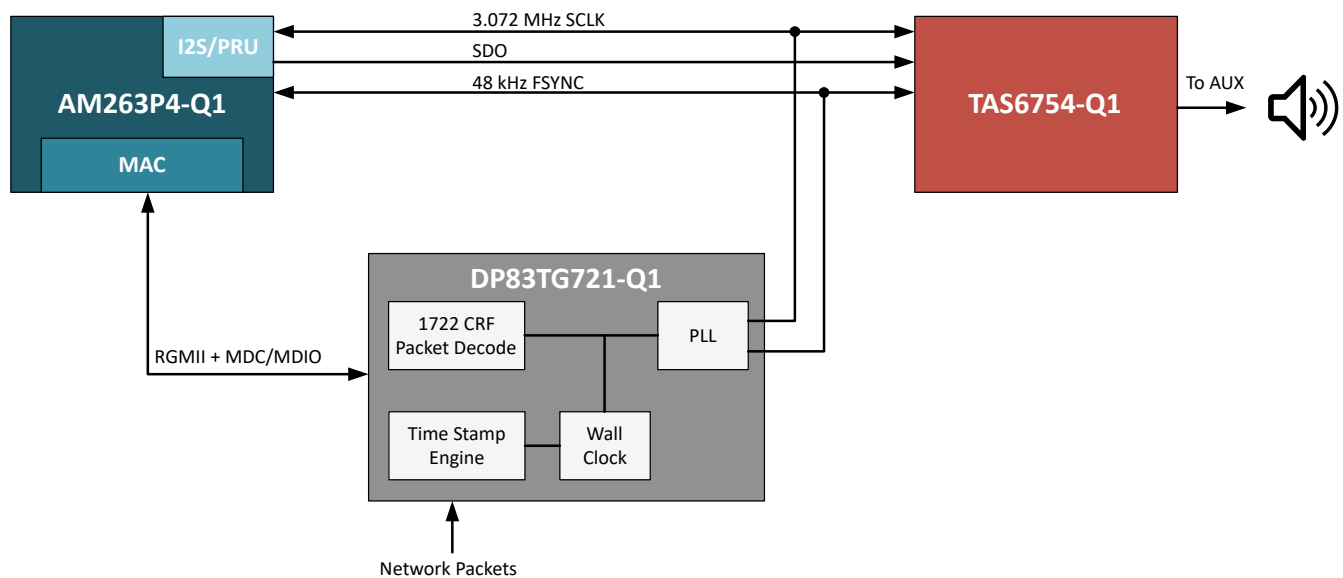


Figure 11. TI's AVB solution using the AM263P4-Q1, DP83TG721-Q1 and TAS6754-Q1

Table 3 lists protocols for an Ethernet ring architecture and AVB.

Protocol	Description
IEEE802.1AS	Defines synchronization of local clocks to a grandmaster clock (gPTP)
IEEE802.1Qav	AVB stack and traffic scheduling for TSN
IEEE1588	Two-way exchange of time stamped messages Precision Time Protocol Best master clock algorithm
IEEE802.1Qbv	Enhancements for traffic scheduling
IEEE802.1cb	Packet duplication Packet forwarding Duplicate package rejection Ring termination
IEEE1722	AVB transport protocol for media clock recovery

Table 3. List of protocols for an Ethernet ring architecture and AVB

Conclusion

As automakers migrate toward centralized architectures, reliable, efficient and scalable network architectures become increasingly important. Implementing Ethernet ring architectures enhance vehicle reliability by providing redundant data streams between ZCMs and the CCUs. Furthermore, TSN enables the integration of diverse data streams, including audio through AVB, onto the Ethernet backbone, optimizing network wiring costs.

Additional resources

- Learn more about TSN and other applications in the technical white paper, "[Time Sensitive Networking With Ethernet PHY](#)."
- Check out the [Arm Cortex-R MCU](#) page and automotive Ethernet PHY options on the [Ethernet ICs](#) page.
- Watch the video, "[Automotive Ethernet Ring Network Demonstration](#)."

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