Poster: Potentials of Mixing TSN Wired Networks and Best-Effort Wireless Networks for V2X

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***Abstract*—Cooperative Connected and Automated Vehicles (CAVs) require multiple disjunct In-Vehicle Networks (IVNs) to interact via wireless networks, making communication across vehicles prone to unnecessary queuing delays. Earlier studies have focused on updating wireless networks to integrate with IVNs, which would require substantial changes to the core and access network. In this work, we motivate an approach that moves complexity to the network edge, examining the potentials of mixing Time Sensitive Networking (TSN) wired networks and unmodified, best-effort wireless networks for Vehicle to Everything (V2X). Guided by a platooning use case, we present results from a simple proof-of-concept system simulation demonstrating the potentials of such an approach as well as the feasibility of performance evaluation in openly available simulation frameworks.**

I. Introduction

Cooperative Connected and Automated Vehicles (CAVs) are integrating hundreds of Electronic Control Units (ECUs) forming complex In-Vehicle Networks (IVNs). Generally, IVNs have stringent system and communication requirements such as guaranteeing deterministic and low end-to-end latency (from tens of µs up to tens of ms). In these networks, data production needs to be tightly synchronized with data consumption in order to reduce latency and jitter. In this context, Time Sensitive Networking (TSN), which provides a set of standards and protocols for deterministic communication – i.e., for flow synchronization, management, control, integrity – has been identified as a promising technology for an automotive profile, such as by the IEEE 802.1DG task group.

So far, TSN-based IVNs have been designed considering vehicles as isolated networked systems with a predefined network topology. Nowadays, however, local IVNs are routinely becoming part of larger networks spontaneously created via Vehicle to Everything (V2X) communications, which rely on both wired TSN networks and best-effort wireless V2X technologies, such as IEEE 802.11p and Cellular V2X (C-V2X). In such hybrid networks, there is no guarantee that a local IVN of a vehicle will immediately deliver an incoming time-sensitive message generated by an ECU located in a neighboring vehicle's IVN.

Typically, when merging multiple TSN networks, there are two main challenges to be addressed: time synchronization and data traffic scheduling. Most of the earlier related work focuses on the time synchronization aspect. For example, Lee and Park [1] were among the first to motivate the necessity of connecting multiple IVNs via IEEE 802.11p wireless links.

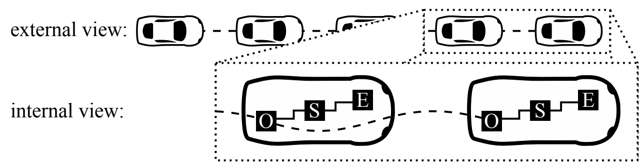

Figure 1. Platoon example with tightly integrated TSN-based IVNs across best-effort wireless network.

Nasrallah et al. [2] provide a comprehensive description of the IEEE TSN standards and survey the existing literature that targets ultra-low latency in 5G. They argue about the importance of extending TSN to support external network interaction and propose to use hierarchical controllers to extend in-vehicle to external networks. Haxhibeqiri et al. [3] and Romanov et al. [4] propose mechanisms that extend the TSN time synchronization to IEEE 802.11-based wireless networks. Gundall et al. [5] and Wang and Sun [6] design solutions to integrate the TSN time synchronization with 3GPP systems. Finally, Fernández et al. [7] tackle the scheduling problem and design a hybrid wired/wireless centralized architecture for industrial control applications. They propose a new Medium Access Control (MAC) protocol based on the IEEE 802.11 physical layer.

A major drawback of these earlier studies is that they propose to make the core and access networks part of a TSN (e.g., reserving end-to-end circuits, dedicating specific nodes to act as gateways, or redesigning the MAC protocol of the wireless network). This would require substantial changes to the core and access network to work. Instead, we argue that a more realistic approach is to move complexity to the network edge and make TSN driven IVNs work across best-effort wireless networks. In more detail

- we examine the issues arising from unsynchronized IVNs;
- we demonstrate the potential of synchronized IVNs schedules over a plain IEEE 802.11p connection; and
- we show first insights from a simulative study using well-established simulators (OMNeT++, INET, Plexe, Veins).

II. Proof-of-Concept Study

To illustrate the proposed concept, we focus on the vehicular platooning use case, that is, convoys of cooperative autonomous vehicles exchanging sensor and maneuver information on a tight schedule, thus allowing for the whole platoon to act as one vehicle and – by extension – to drive with small inter-vehicle gaps (see Figure 1, external view). As the simplest example of a

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TSN-based IVN, each vehicle in the platoon is composed of just three elements: (i) an ECU acting as data producer/consumer, (ii) an On Board Unit (OBU) connected to the IVN as well as to other vehicles via regular V2X communication technology (e.g., IEEE 802.11p or C-V2X), and (iii) a Switch connecting the two devices (see Figure 1, internal view).

To maintain the platoon formation, vehicles send periodic broadcast messages containing control data. These messages are produced and consumed by the respective ECU, hence must traverse the producer IVN, the wireless network, and the consumer IVN (i.e., ECU$\xrightarrow{\text{Switch}}OBU\xrightarrow{\text{V2X tech.}}OBU\xrightarrow{\text{Switch}}$ECU). Ideally, the production schedule of control data is coordinated with not just the producer IVN, but also with the wireless network and the consumer IVN, thus minimizing delay and avoiding issues associated with stale data.

For our proof-of-concept study, we use a simulation framework built on the OMNeT++ 6.0pre11 discrete-event simulator together with the simulation module libraries of INET v4.3.0-269-g0612f3572d (which contains TSN functionality), Plexe 3.0, and Veins 5.1 [8]. We modify these to work with each other as well as for disjunct and dynamic network topologies.

We simulate a platoon of five vehicles controlled by Cooperative Adaptive Cruise Control (CACC) that only uses data communicated by the vehicle in front [9]. Vehicles send periodic 154 Byte-long control messages – every 100 ms – over IEEE 802.11p V2X wireless links.

We model each IVN as a TSN-enabled 100 Mbit/s Ethernet network. Our experiment includes a realistic implementation of the TSN Time-Aware Shaper (TAS) mechanism, with a global gate cycle period of 100 ms. Gate scheduling is performed dynamically at run time by an oracle, based on the network topology and a set of streams. Each stream is characterized by priority, source, destination, packet length, and packet interval.

The experiment starts with all five vehicles already in a platoon, but each of the five IVNs still configured independently and all vehicles' ECUs producing control data at the same time. In particular, let $i = 1, .., 5$ be the vehicle index, with $i = 1$ being the index of the platoon leader. We configure exactly two TSN streams for each IVN: (i) from ECU_i to OBU_i, for outgoing messages, and (ii) from OBU_{i+1} to ECU_{i+1} for incoming messages. This represents the default configuration, in which IVNs are not aware of each other. Then, we let IVNs join one by one, every $t = 1$ s. Specifically, IVN_i and IVN_{i+1} are joined by replacing the aforementioned pair of individual streams with a new stream that goes from ECU_i to ECU_{i+1} taking special care to model that this stream crosses a shared, best-effort wireless medium.

The results are illustrated in Figure 2, which shows the end-to-end delay of control messages between consecutive IVNs, measured as the time difference between message generation (by ECU_i) and reception times (by ECU_{i+1}). It can be noticed that when IVNs are not synchronized, the latency is 100 ms. This is because messages have to queue for medium access, hence when messages from ECU_i finally reach Switch_{i+1}, the output gate has just closed (i.e., the sending opportunity for the current gate cycle has been missed), meaning that messages have to wait for the next open gate opportunity which can be at most equal to a full gate cycle period. As soon as an IVN_{i+1} of a vehicle is synchronized with the IVN_i of the preceding vehicle, the delay decreases substantially (from up to 100 ms to below 1 ms in our case). This is because data production at vehicle i is now tightly synchronized with the wireless network as well as the consumer IVN.

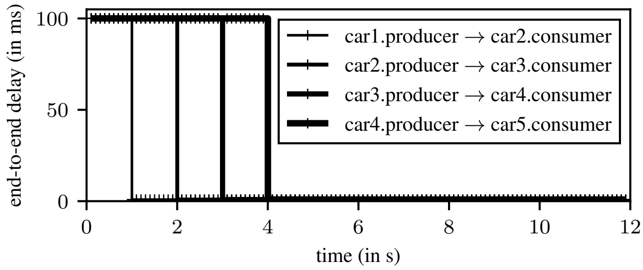

Figure 2. End-to-end delay of control messages between consecutive vehicles.

III. Conclusion and Future Work

In this paper, we examined the potentials of mixing Time Sensitive Networking (TSN) wired networks and unmodified, best-effort wireless networks for Vehicle to Everything (V2X). Guided by a platooning use case to demonstrate the benefits of such an approach, we presented results from a simple proof-of-concept system simulation demonstrating the feasibility of performance evaluation in openly available simulation frameworks. This is fertile ground for multiple lines of research. Potential next steps are the construction of centralized, then distributed scheduling algorithms, then expanding this to multiple platoons and/or to accommodate background traffic.

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