Dynamic Service-Orientation for Software-Defined In-Vehicle Networks

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Abstract—Modern In-Vehicle Networks (IVNs) are composed of a large number of devices and services linked via an Ethernet-based time-sensitive network. Communication in future IVNs will become more dynamic as services can be updated, added, or removed during runtime. This requires a flexible and adaptable IVN, for which Software-Defined Networking (SDN) is a promising candidate. In this paper, we show how SDN can be used to support a dynamic, service-oriented network architecture. We demonstrate our concept using the SOME/IP protocol, which is the most widely deployed implementation of automotive service-oriented architectures. In a simulation study, we evaluate the performance of SOME/IP-adaptive SDN control compared to standard Ethernet switching and non-optimized SDN. Our results show an expected overhead introduced by the central SDN controller, which is, however, reduced by up to 50% compared to SOME/IP-unaware SDN. For a large number of services, the setup time is in the order of milliseconds, which matches standard Ethernet switching. A SOME/IP-aware SDN controller can optimize the service discovery to improve adaptability, robustness, security, and Quality-of-Service of the IVN while remaining transparent to existing SOME/IP implementations.

Index Terms—SDN, In-Vehicle Networks, Service-Oriented Architectures, SOME/IP, Service Discovery

I. INTRODUCTION

Today's vehicles accommodate a large number of interconnected Electronic Control Units (ECUs), the software of which is expected to undergo faster development cycles with frequent updates and service reconfigurations. The introduction of a Service-Oriented Architecture (SOA) promises to support this increasing dynamic [1]. The In-Vehicle Network (IVN) plays a fundamental role in the performance, safety, and security of these interconnected services [2]. Ethernet emerges as the next generation IVN technology to extend capacity and flexibility, while replacing existing bus systems. Time-Sensitive Networking (TSN) enhances Ethernet with Quality-of-Service (QoS) features, e.g., deterministic communication and redundancy.

One major challenge of future IVNs is to transform from statically pre-configured into service-oriented networks that support dynamic service adaptation. With its centralized control plane, Software-Defined Networking (SDN) promises a dynamic and flexible IVN [3]. In previous work, we presented Time-Sensitive Software-Defined Networking (TSSDN) that supports QoS and security requirements of in-vehicle applications [4], [5]. An SDN controller can reconfigure the network according to service availability, including updates or failures. TSN resource partitioning [6] allows adding new traffic flows dynamically without affecting a static configuration defined at

design time. Additionally, failover mechanisms and seamless service mobility [7] can improve the robustness of the IVN.

Evolving automotive systems is challenging, as industry practices and backward interoperability need to be met at reasonable overhead [2]. The *Scalable service-Oriented MiddlewarE over IP* (SOME/IP) is a widely used protocol for automotive SOAs standardized by AUTOSAR [8]. SOME/IP offers Service Discovery (SD) [9] as a complementary service. SDN-supported SOA in vehicles opens powerful potentials. Options range from discovery optimizations to QoS, security, and robustness improvements. To support in-car SOA, the SDN controller must know all services on the IVN, and thus support automotive protocols for service discovery.

In this work, we present a network control scheme for the SOME/IP SD based on the SDN paradigm. We design an SDN controller application that fully supports SOME/IP SD. It intercepts discovery messages, learns about services, directly responds to requests, and sets up paths automatically. Our approach is completely transparent to existing SOME/IP implementations. We discuss further potentials of supporting SOME/IP communication with SDN (service discovery optimization, service mobility, QoS improvements, discovery protection). In simulation, we compare the scalability of our approach to non-optimized SDN and standard Ethernet.

The remainder of this work is structured as follows: In Sec. II, we discuss related work. Sec. III introduces the SOME/IP SD mechanism, the SDN paradigm, our methodology to support automotive SOAs with SDN, and further potentials enabled by their combination. Sec. IV evaluates the performance of the proposed SDN supported SOME/IP SD. Finally, Sec. V concludes this work and outlines future work.

II. BACKGROUND AND RELATED WORK

Today, an IVN is a complex distributed system with a multitude of devices and services communicating via a combination of bus systems and switched Ethernet. Combined with Time-Sensitive Networking (TSN), Automotive Ethernet is a promising candidate for the backbone of next generation IVNs. Gateways that translate between different networks (e.g., CAN and Ethernet) and protocols are commonly used to enable interoperability and backward compatibility [10].

A. Service-Oriented Architectures in Vehicles

SOA is proposed to enable flexible and dynamic application placement, and frequent updates in automotive networks [1].

In-vehicle applications can act as service providers to make certain functions and data available to consuming applications. While dynamic service discovery can improve flexibility of, for example, navigation, infotainment, diagnostics, and driver assistance services, safety-critical services may still require dedicated, static connections to ensure reliability [11].

Two major candidates are considered as the communication protocol for SOAs in vehicles [10]: (1) SOME/IP [8] is explicitly tailored to the automotive environment and enables service-oriented communication via TCP/UDP-IP. (2) Data Distribution Service (DDS) [12] from the Object Management Group is a viable alternative available in the AUTOSAR platform, but not designed for automotive applications and not widely used by automotive companies [10]. This work focuses on SOME/IP due to its widespread deployment in the automotive domain. Nevertheless, our work translates to other protocols such as DDS.

In previous work [11], we assessed the design space of vehicular services and proposed a mechanism to enable QoS within a vehicular middleware. Since rollout of SOME/IP-SD in AUTOSAR 4.1, SOA is a standard feature for future IVNs. Kampmann et al. [13] propose containerized services to be placed and activated on dynamic allocated hardware resources during runtime. The dynamic nature of SOAs poses challenges to a traditionally pre-configured IVN, as it must adapt to changes in service availability during runtime.

B. Supporting Automotive Network Functions with SDN

Software-Defined Networking (SDN) has the potential to increase the flexibility and performance of networks [14], in particular in well-known environments. SDN centralizes the control plane and separates it from the data plane, allowing a central controller to perform network functions such as routing, firewalling and load balancing for the local network.

In cars, SDN can enable a reconfigurable and flexible network architecture that adapts to changes in the network, e.g., software updates and downloadable drive assistance systems [3]. In previous work [4], [5], we presented TSSDN, an integration of SDN with TSN, and showed how SDN can significantly enhance IVN security. Ergenç et al. [7], illustrate service-based resilience for IVNs by configuring backup nodes for critical services. In case of failures, those can be activated, which also requires changes in the network configuration.

Intercepting packets of network control protocols is a common approach to optimize networking objectives via SDN. Examples include the management of the Address Resolution Protocol (ARP) [15] or IP multicast routing [16]. Bertaux et al. [17] present a first design for an SDN application that dynamically allocates network resources for DDS applications. Such a mechanism is missing in SOME/IP and could enable the IVN to adapt to changes during runtime.

In this work, we present a concept for an SDN controller application that fully supports the SOME/IP SD protocol. It can intercept and handle service announcements and subscriptions to manage network resources but remains fully transparent for existing SOME/IP implementations and applications.
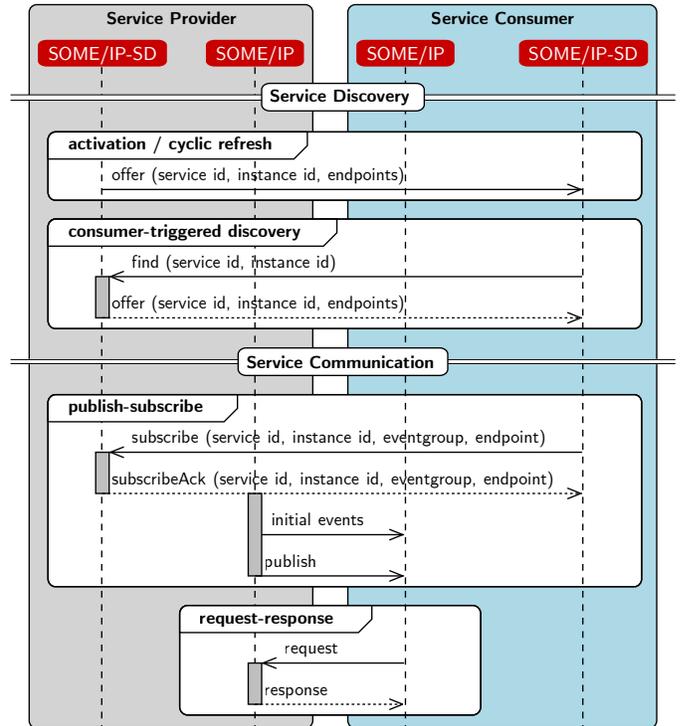

Fig. 1: SOME/IP service discovery and communication.

III. SDN-Supported SOME/IP Service Discovery

Our concept applies the SDN paradigm to service-oriented in-vehicle communication using the SOME/IP protocol. First, we introduce the SOME/IP SD mechanism, next our methodology to support automotive SOAs with SDN, and finally cover SOME/IP message handling in a controller application.

A. The SOME/IP Service Discovery

The AUTOSAR SOME/IP protocol [8] includes a Service Discovery (SD) protocol [9] with an offline-defined endpoint (IP multicast group / UDP port) on each device. Fig. 1 shows a sequence with SOME/IP SD and service communication.

SOME/IP has two message types for service discovery: `find` to request a service, and `offer` to announce a service. Providers send an `offer` to the SD multicast group upon service activation or as a cyclic refresh. A consumer can initiate a `find`-request for a service as a SD multicast. Multiple instances of the same service can coexist in a vehicle. All providers of the requested service respond with an unicast `offer`. A SOME/IP service identifies with service ID, instance ID, and major/minor version. The instance ID, major/minor version can be wildcarded in the `find`-request if any instance of the specified service ID is applicable.

Discovered services can communicate following a publish-subscribe or a request-response model. For the latter, a consumer requests a data field or method from a provider via unicast each time the data is needed and awaits the response. In the publish-subscribe model, a consumer subscribes once to a service instance via unicast to be notified repeatedly. The provider acknowledges the subscription and communication
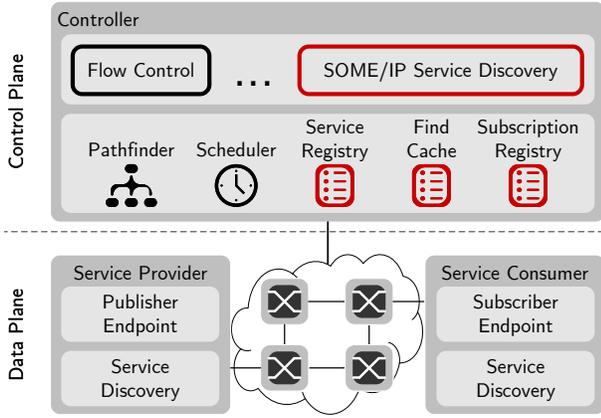
Fig. 2: Concept for an SDN-supported automotive SOA. Components in red are added, others remain unaltered.

TABLE I: Handling SOME/IP service discovery messages on the control plane depending on the state – *known* when in the service registry, *requested* when in the find cache, and *subscribed* when in the subscription registry.

Message	State `(X)`	Reaction
`find(X)`	*Known*	respond with `offer`
	Not *known*	Send `find` to multicast group
`offer(X)`	*Requested*	Update service registry, forward to requester or multicast group
	Not *requested*	Update service registry, forward to multicast group
`subscribe(X)`	*Known*	Update subscription registry, forward to provider
	Not *known*	Send negative acknowledgement
`subscribeAck(X)`	*Subscribed*	Update subscription registry, install forwarding, forward to subscriber
	Not *subscribed*	No handling

endpoints are created. The provider can then send initial events and thereafter publish updates on-change or periodically.

A Time to Live (TTL) field is used to limit the lifetime of an `offer`, `find`, or `subscribe`. To withdraw an offered service or subscription, the message is sent with identical service ID and instance ID, but with the TTL set to 0.

B. Architecture of an SDN-Supported Automotive SOA

We integrate the SOME/IP service management with SDN, enabling the SDN controller to gather information about SOME/IP services and exploit it for network optimization. Fig. 2 gives an architectural overview of the proposed concept.

The network is divided into control plane and data plane following the SDN paradigm. On the data plane, switches connect service providers and consumers and forward packets between endpoints based on their forwarding tables. The SDN controller on the control plane manages the network and the forwarding tables of network devices.

We add a specialized network application to the SDN controller that intercepts all SOME/IP SD messages and extracts information about the services. It stores this information in three SD tables: (1) A service registry that contains all known service instances and their endpoints. (2) A find cache stores all open `find`-requests which the controller can only answer after the service was discovered. (3) A subscription registry tracks subscriptions and their status (e.g., active or subscription requested) for the publish-subscribe model.

C. Controlling the SOME/IP Service Discovery with SDN

Table I shows how the controller application handles SOME/IP SD messages depending on the state of the three SD tables. The controller responds directly to `find` messages for registered services and sends all known instances of a service ID when the instance ID is a wildcard. If the service instance is not yet known, the `find` is cached and forwarded to the multicast group. On `offer` messages, the controller updates the service registry. If the `offer` is sent as a direct reply to a cached `find` it is forwarded to the requester, otherwise to the multicast group.

All `subscribe` messages are forwarded to the provider. If the service is known, they are added to the subscription registry. When the controller receives a `subscribeAck` and the subscription is in the table, it installs a forwarding rule. Then it forwards the message to the subscriber. For subscriptions that are already active (e.g., in case of multicast), the controller updates existing rules along the path.

Withdrawn offers are updated in the subscription and service registry and forwarded to the multicast group. Withdrawn subscriptions are updated in the subscription registry and forwarded to the service provider. Previously installed rules must also be removed or updated in forwarding devices.

These mechanisms are fully transparent towards the endpoints and do not require any changes in the SOME/IP SD protocol implementation nor the applications Introducing a central network controller, however, impacts service discovery performance, since all SD messages are forwarded to the controller, which we evaluate in Section IV.

D. Potentials of SDN-Supported Automotive SOA

Further potentials emerge if the SDN controller is aware of the SOME/IP SD protocol:

1) Optimized service discovery: The controller can automatically install flows and efficiently add new subscribers to multicast flows after receiving a `subscribeAck` message. Furthermore, load on the data plane could be reduced by directly forwarding SD messages to the known SOME/IP endpoints, skipping links between forwarding devices. With SDN, any Ethernet topologies such as rings can be supported for SOME/IP services, enabling load balancing and redundancy.

2) Seamless service mobility: The controller can seamlessly reconfigure publishers and subscribers, as they move from one device to another without disrupting communications. In addition, it can hand over subscriptions from one publisher instance to another instance of the same service if the original publisher fails. Other reconfiguration mechanisms could improve the robustness of the IVN, such as the fast handover in case of a link failure.

3) Quality-of-Service enforcement: The IVN has strict QoS requirements with particular real-time capabilities. In traditional networks, it can be challenging to translate QoS requirements of application layer services onto the underlying link layer. Already on host devices, preconfigured mapping from network layer QoS options to link layer QoS options is required. Communicating such requirements to the network can be even more challenging. In the proposed approach, the controller can enforce QoS requirements of the subscriber in the network. In previous work, we have shown how a central controller can configure the TSN-scheduling of switches [5].

4) Discovery protection: While IVN security is imperative for ensuring vehicle safety, in-vehicle communication protocols and architectures often lack security mechanisms [2]. In the case of SOME/IP, end-to-end encryption can be used to protect the message payload. However, the discovery of SOME/IP services is not protected, and malicious nodes could easily spoof the discovery messages, e.g., to announce conflicting publisher service instances or add additional subscriptions to increase the network load. The controller can support security mechanisms for SOME/IP SD to verify the authenticity of discovery messages and control access policies for providers and consumers.

IV. Performance analysis

Our study compares the performance of the presented concept compared to non-optimized SDN forwarding and standard Ethernet switches in simulation. Our key performance metric is the time to set up all subscriptions in a network, from first producer until the last subscription is established.

A. Simulation Environment

Our simulation environment is based on the OMNeT++ simulator [18] with the INET framework, and the OpenFlowOMNeTSuite [19]. For our implementation, we use the CoRE4INET, SDN4CoRE [20], and SOA4CoRE [11] frameworks which our research group maintains. They are open source on *github.com/CoRE-RG*. SOA4CoRE implements the SOME/IP and SOME/IP SD protocol, and our proposed controller application for SOME/IP SD is added to SDN4CoRE.

B. Evaluation Scenario

Fig. 3 shows the topology used for the comparison. It consists of switches, producer nodes, and consumer nodes connected via $1\,\mathrm{Gbit/s}$ Ethernet links. All switches are connected to a controller in the SDN variants.

To investigate scalability, we vary the number of producer (P) and consumer nodes (C) from 1 to 50, and the number of switches between them from 1 to 5, since we expect that this number is not exceeded in a real IVN. Each producer has one publisher service. Each consumer has one subscriber service per publisher. We simulate all 192 parameter combinations and measure the time to set up all subscriptions.

The simulation models provide a wide range of configuration parameters. Switches have a hardware forwarding delay of $8\,\mu\mathrm{s}$. The SDN controller uses the OpenFlow protocol to
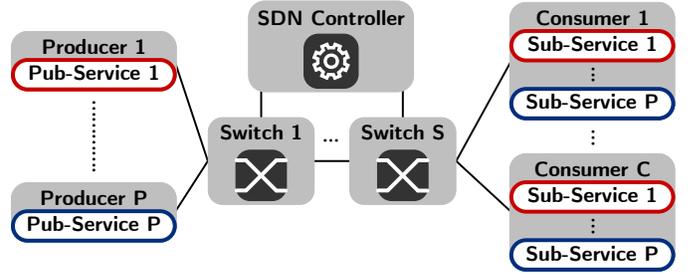

Fig. 3: Topology for the scalability comparison with 1 to 5 switches (S), 1 to 50 producers (P), and 1 to 50 consumer nodes (C) with one subscriber service per producer (P).

configure the switches. The OpenFlow messages processing time in the controller application is $100\,\mu\mathrm{s}$, based on the worst-case performance of the best-performing controller implementation we have evaluated in previous work [21]. We assume the switch processing time is similar and set it to $100\,\mu\mathrm{s}$, but could not find any data in the literature on the performance of OpenFlow processing on switches. The controller and the switches can handle multiple OpenFlow packets in parallel.

C. Results

Fig. 4 compares the setup time of the presented approach (SDN optimized), non-optimized SDN forwarding (SDN vanilla), and standard Ethernet (w/o SDN) for 1 to 50 producers on 1, 2, and 5 switches on a logarithmic scale. For simplicity, the graphs only depict results for 1 and 50 consumers per producer, the others show a similar trend.

In all cases, we observe an approximately linear increase in setup time with the number of producers for all three approaches. Compared to standard Ethernet switching, the SDN solutions are about one order of magnitude slower, which is to be expected due to the delay caused by forwarding each SOME/IP SD packet to the central SDN controller. This delay is highly dependent on the OpenFlow processing time. Optimized controllers, and switches might come closer to the Ethernet performance. Nevertheless, the additional delay only affects the setup time of the subscriptions and not the actual data transfer of the service.

For setting up one subscription over 5 switches, the optimized SDN approach takes $0.6\,\mathrm{ms}$, non-optimized SDN $2.2\,\mathrm{ms}$ and the non-SDN variant only $0.1\,\mathrm{ms}$. This is a good indicator that the time to migrate a service from one node to another is less than $1\,\mathrm{ms}$. The setup of subscriptions for 50 publishers with 50 subscribers each (2500 subscriptions), is considered a cold start as all services announce their availability and their required subscriptions at the same time. The setup for all connections takes about $5.5\,\mathrm{ms}$ without SDN, $16.4\,\mathrm{ms}$ with vanilla SDN, and $9.3\,\mathrm{ms}$ with our optimized SDN approach.

Overall, the presented approach of a SOME/IP-aware SDN controller improves performance by up to 50% compared to a non-optimized SDN. Although a migration time of $1\,\mathrm{ms}$ is acceptable for most in-vehicle services, it may not be acceptable for safety-critical services, e.g., collision detection, which likely require configured routes and redundancy. Most
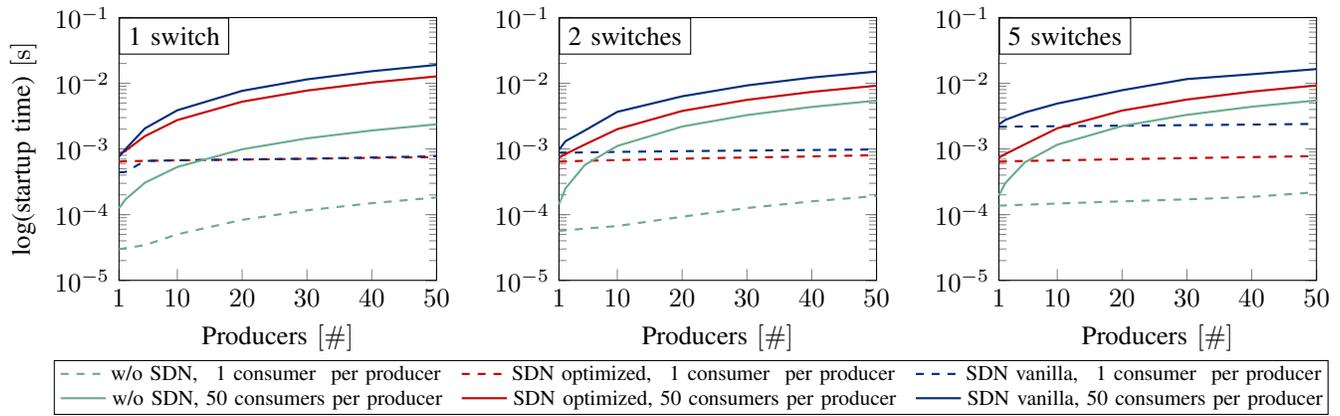
Fig. 4: Comparison of the presented approach (SDN optimized) to non-optimized SDN forwarding (SDN vanilla) and standard Ethernet switches (w/o SDN) in terms of scalability. The logarithmic scale depicts the total time to set up all subscriptions for an increasing number of producers with 1 and 50 consumers per producer.

services, however, are discovered when the vehicle is started. The fastest required service availability in current cars is about $200\,\text{ms}$ and even lower for, e.g., infotainment services. Therefore, the setup time for all in-vehicle connections (2500 services in less than $10\,\text{ms}$) is acceptable for all kinds of services, including safety-critical services.

V. CONCLUSION AND OUTLOOK

This paper proposed an SDN-based network control scheme for SOME/IP SD. We designed an SDN controller application that fully supports SOME/IP SD, while remaining transparent to existing SOME/IP implementations. The controller detects available service instances and automatically sets up paths in forwarding devices for acknowledged subscriptions.

We evaluated the performance of our approach in a simulation-based study, comparing its scalability to non-optimized SDN and standard Ethernet switching. Our approach improved the SDN performance by up to 50% compared to the non-optimized SDN solution. The central controller processing all SOME/IP SD messages significantly reduces SDN performance, but the additional delay only affects subscription setup time, not the actual data transfer. Our approach achieves a setup time below $10\,\text{ms}$ for 2500 subscriptions, complying with the fastest service availability normally required in a vehicle, which is about $200\,\text{ms}$.

We explored various potentials and extensions of a SOME/IP SD-aware SDN controller. Future work will focus on further optimizing service discovery, mobility, and reconfiguration mechanisms for improved robustness, QoS support, and security enhancements.

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