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Service-actuated multi-channel operation for vehicular communications

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A B S T R A C T

We present a novel approach for multi-channel operation (MCO) in vehicular communication systems, which allows for efficient utilization of the available bandwidth by asynchronous channel switching and enables dynamic service provisioning and usage by means of service advertisements. The proposed solution – Service-Actuated Multi-Channel Operation (SAMCO) – provides a logic that controls the prioritization of services and the timing of channel switching. It takes into account users preferences to decide on the consumption of a particular service if several concurrent services are available. SAMCO employs a novel channel load estimation scheme that, in addition to measuring the load on the channel at the physical layer, exploits the information contained in service advertisements. We perform simulations and use platooning as an example of a service with particularly stringent requirements to show that SAMCO can support service prioritization, continuity of service for high-priority services, and graceful degradation for low-priority services. Furthermore, by limiting the admission to services in high load scenarios, we show that SAMCO effectively controls the channel load and thereby complements congestion control mechanisms. Finally, we discuss the extensions needed in currently standardized solutions to implement SAMCO.

1. Introduction

Vehicular communication is expected to enable many safety, traffic efficiency and infotainment applications and services[1]. The communication can take many forms, including Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Pedestrian (V2P) – in short, they are called V2X. Currently, standardized solutions for Vehicular Ad Hoc Networks (VANETs) – i.e., networks which do not need additional infrastructure for successful communication – are based on short-range wireless communication using IEEE 802.11p/ITS-G5 set of standards [1][2]. The architecture and protocols for such Cooperative Intelligent Transport Systems (C-ITS) have been standardized in Europe by ETSI TC ITS (ITS-G5) [2] and in the U.S. by IEEE [3]. This first release of V2X communication systems targets applications for road hazard warning, collision avoidance, speed management and others [4]. The next release considers cooperative automated driving, in particular for Cooperative Advanced Cruise Control (CACC) and platooning, where the communication supports the exchange of sensor data and maneuvering commands among vehicles [5]. It is assumed that architecture and protocols from the first release can be extended in the next releases to support communication for automated driving.

For the purpose of road safety and traffic efficiency, VANETs primarily operate in the 5.9 GHz frequency band. By regulation, this spectrum is split into several wireless channels of 10 MHz bandwidth. In order to efficiently utilize the spectrum, vehicles need to operate on multiple channels simultaneously, referred to as multi-channel operation (MCO).

The IEEE 1609.4 standard [6] provides a flexible framework for MCO in the IEEE 1609 protocol stack. It relies on channel switching or alternating between a Control Channel (CCH) and Service Channels (SCHs) for single-radio transceivers, and between SCH for dual-radio transceivers; the latter when considering that one radio is constantly tuned in the CCH. Service advertisement messages

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[1] In the remainder of the text, we use the terms application and service interchangeably.

[2] The 'p'-amendment to IEEE 802.11 for inter-vehicular communication has been integrated into the 2012er version [1]. ITS-G5 is the European variant derived from it.

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(SAMs) are broadcast on the CCH[3] in order to inform neighboring vehicles about available services in the vicinity. In addition to the IEEE 1609.4 standard, *simTD* [7], one of the major field trials for inter-vehicular communication completed in 2014, has developed an architecture and message formats for MCO, but this solution has not been transferred to the European standardization process yet.

Compared to single channel usage, MCO provides advantages in terms of higher throughput by offloading data traffic from the CCH to SCHs. When the load on the CCH is kept below a critical threshold, MCO can improve the spectral efficiency. As a result, channel switching allows to cope with varying load conditions that can be experienced because of dynamically activated services, vehicle mobility and frequent changes in network topology. However, the improved performance increases the system complexity since it requires a system function for channel switching and, in particular in the case of dual-radio transceivers, results in higher device costs. The design of a MCO solution is challenging due to the specific characteristics of VANETs. The decentralized organization of VANETs and their dynamic and ephemeral characteristics create challenges in protocol design, where nodes only have local information available for decision making. Most applications for road safety and traffic efficiency have distinct functional and stringent performance requirements, which MCO must support.

MCO can be enabled by single or dual-radio transceivers. Although the initial release of inter-vehicular communication systems is based on single-radio transceivers in vehicles, it is expected that the next generations of the system will rely on dual-radio transceiver settings for improved performance. For communication in support of automated driving, such as platooning, the communication requirements are more stringent than in the first release and therefore, efficient and effective MCO becomes a necessary system function. Furthermore, in addition to services offered by roadside units to vehicles (I2V) envisioned in the initial release (e.g., intersection information and control, probe vehicle data services, etc.), for automated driving it is foreseen that channel switching will be used for inter-vehicle (V2V) services, where one vehicle (e.g., platoon leader) provides service to other vehicles (platoon members).

The existing IEEE 1609.4 standard for MCO provides a flexible framework for channel switching, but does not define the logic for service provisioning and usage. In particular, mechanisms to ensure service continuity for high priority service and graceful degradation of low priority services are beyond the scope of the standards. Also, the standard is static in terms of channel load, i.e., it does not take the actual channel status into account when a channel switch is executed.

In this work we rely on the architecture and message format of the MCO solution in the simTD project and propose SAMCO (Service-Actuated Multi-Channel Operation), a lightweight channel switching algorithm that is aware of applications requirements and channel load. Our design goals for SAMCO are: (i) continuity for high priority services, (ii) graceful degradation of lower priority services as channel load increases, (iii) user-based prioritization of services, and (iv) minimizing the channel switching frequency, which is directly related to the number of times an application is moved to another channel. SAMCO improves the performance of time-critical applications, which are exemplified by platooning – a representative use case of partially automated driving with stringent performance requirements – in the presence of multiple concurrently available services of different priorities.

The contributions of this work are as follows:

[3] SAMs can also be sent on a default service channel, as it is currently considered in the standardization process in Europe and the U.S., however, the principles are the same.

Table 1
ITS-G5 channel allocation (ETSI EN 302 636 [8]).

Band	Channel	IEEE channel	Frequency (GHz)	Bit rate	TX power (dBm)
ITS-G5B	SCH4	172	5.86	6	0
ITS-G5B	SCH3	174	5.87	6	23
ITS-G5A	SCH1	176	5.88	6	33
ITS-G5A	SCH2	178	5.89	12	23
ITS-G5A	CCH	180	5.90	6	33

- We propose a practical, dynamic channel switching algorithm that takes into account the (estimated) channel load, existing services on channels, and user preferences. We supplement the switching algorithm with an implicit channel load estimation algorithm and the corresponding service announcement protocol.
- We provide a framework for MCO that allows incorporating future services with different priorities and requirements.
- We assess the performance of the proposed MCO solution for the platooning use case by means of simulation and show that the MCO solution increases the proportion of successfully served platoons, while it also helps the non-platooning applications.

The remainder of this article is structured as follows. Section 2 provides technical background on MCO and on platooning, respectively. The proposed MCO algorithm is presented in Section 3, followed by a description of the evaluation scenario and environment in Section 4, the performance evaluation results for the platooning use case in Section 5, and the conclusions in Section 6.

2. Background

This section provides technical background and briefly reviews the state-of-the-art for MCO and platooning.

2.1. Multi-Channel Operation

The need for MCO originates from the spectrum allocation in the 5.9 GHz range for safety and non-safety data exchange and the simplified ad hoc mode (Outside the Context of a BSS, OCB) in IEEE 802.11p/ITS-G5. In Europe, a 50 MHz spectrum is divided into two frequency bands, i.e., *ITS-G5A* for safety-related services (CCH, SCH1, SCH2) and *ITS-G5B* for non-safety related services (SCH3, SCH4) with 10 MHz channels each (see Table 1). The CCH is, despite its misleading name, used to transmit critical safety data, in particular the periodic safety message, Cooperative Awareness Message (CAM) in the European C-ITS protocol stack. Since in the initial deployment phase of V2X communication the load on the CCH will be rather low due to the slowly growing penetration rate of V2X communication equipment, is foreseen that the first generation of vehicles will be equipped with a single transceiver operating on the CCH only. With the increasing penetration rate, SCHs can be used to offload data from the CCH. The (quasi-)simultaneous operation on channels requires functional enhancements compared to the single channel case. Specifically, the transmitter needs to route a data packet internally to the intended channel and the receiver has to tune to the right channel in order to receive the packet. MCO schemes are designed specifically for the purpose of coordinating the transmitter and receiver so that both are tuned to the same service channel.

The IEEE 1609.4 standard [6] provides a flexible MCO framework with several deployment options, which enable channel switching or alternating between CCH and SCH for single-radio transceivers, and between SCH for dual-radio transceivers (when

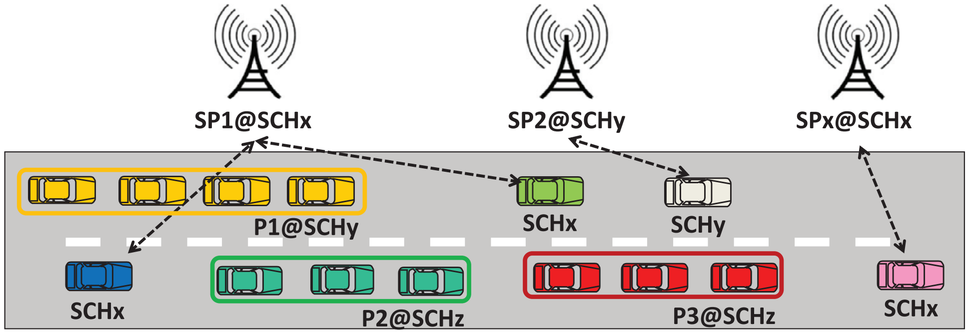

Fig. 1. Typical highway scenario with concurrent services (platooning and non-platooning). The services are executed on different SCHs (x, y and z) and cover vehicle-to-vehicle and vehicle-to-roadside communication.

considering that one radio is constantly tuned in the CCH). Specifically, the standard considers four switching modes for single-radio transceivers: i) *Continuous* when there is no switching and the radio is always tuned on the CCH, (ii) *Alternating* when the transceiver periodically (e.g., every 50 ms) switches between CCH and SCH, (iii) *Immediate* when the transceiver switches between CCH and SCH without waiting until the end of the current channel interval, and (iv) *Extended* when the transceiver switches to the SCH without periodically returning to the CCH. The standard allows to extend the switching modes to dual- (or multiple) radio transceiver configurations.

While the MCO framework has been designed for the IEEE 1609 standard series, the approach can in principle also be applied to the European spectrum allocation and communication system. As the European V2X system relies on an 'always-on safety channel' without using channel intervals, the *Extended* switching mode appears appropriate, however, a mature standard from CEN or ETSI is not part of the release 1.

In order to make channel usage dynamic, the concept of *service* was introduced, which indicates the data that will be exchanged on a service channel. From the various possible solutions for service discovery, explicit signaling to announce the availability of a service is considered; in the IEEE 1609 protocol stack, this is performed by sending a WAVE service advertisement (IEEE 1609.3 [9]), whereas in the European C-ITS stack, a Service Advertisement Message (SAM) (ETSI TS 102 890 [10]) fulfills this role. Therefore, as proposed by the simTD project[4] [7], two roles are defined: service provider (SP) and service user (SU). A typical and simple example is shown in Fig. 1, where a roadside unit (RSU) offers local information on a SCH and periodically broadcasts SAMs. Vehicles receiving the service advertisement then decide whether and how long to use the service. Furthermore, vehicles can also serve as SPs; for example, a vehicle leading a platoon acts as a SP for the platooning service, which it offers to potential members of a platoon (Fig. 1).

In terms of the mechanisms for improving the communications performance in MCO-enabled vehicular communication systems, Campolo et al. [11] survey the existing MCO solutions and enhancements.[5] However, the existing research work is service/application-agnostic, in that it focuses on medium access aspects [12], synchronization [13,14], and related lower-layer performance indicators. In this paper, we design a MCO solution that is able to ensure continuity of high-priority services and graceful degradation of prioritized applications.

2.2. Platooning

Platooning is a specific form of automated driving where vehicles with a common mobility pattern are grouped in order to increase the road capacity. Platoons have very small inter-vehicle distances, which is achieved by eliminating the reacting distance needed for the human driver's reaction. A platoon is comprised of a leading vehicle and followers; the lead vehicle typically acts as master. The complex task of a platoon can be split into basic control functions: *Longitudinal control* adjusts speed and inter-vehicle distance. *Lateral control* deals with vehicle steering, including lane tracking and lane changing. *Maneuver coordination* covers platoon formation (join, leave, merge, dissolve) and the exchange of maneuvering commands.

Cooperative Adaptive Cruise Control (CACC) is one form of platooning, which augments the vehicle sensors by accurate positioning and wireless communication. Typically, it provides longitudinal control only and requires the driver to overtake other driving tasks. Platooning with full automation is commonly referred to as Automated Highway System (AHS) and regarded as long-term solution for platooning. An on-board vehicular platooning subsystem provides longitudinal and lateral control of individual vehicles in the platoon and the coordination among neighboring platoons. Additionally, a roadside platooning system can coordinate the entire road segment, i.e. highway, to route and optimize traffic flows [15,16]. We presume that platooning can be realized by functional extensions of the protocol stack defined in the release 1 of V2X standards [2,3]. The extensions include platooning-specific fields in periodic safety messages (e.g., for the predicted trajectory) and introduce new messages for platoon control, exchange of cooperative maneuvering commands, intersection control, and cooperative sensing [17,18]. To provide a more robust CACC solution, Ploeg et al. [19] propose a control strategy for graceful degradation of CACC service that takes into account impairments inherent in wireless systems (e.g., packet loss). [20] investigates the tradeoff between high-rate platooning messages and other metrics, including latency and data age as well as reliability. Segata et al. [21] discuss control strategies for platooning and identify the message and capacity demands of platoons, with message rates ranging between 10 and 25 Hz per platoon member. Few existing publications (e.g., [18,22,23]), consider platooning messages on service channels, but do not address service provisioning aspects as in this paper.

3. SAMCO: Service-Actuated Multi-Channel Operation

In this section, we present SAMCO, our proposal for a lightweight channel switching scheme. In the proposed scheme, channel switching is driven by the services and applications. This approach is different than in non-safety deployments, such as WiFi-based mesh networks, where channel utilization is the most

[4] http://www.simtd.de , accessed 2016/03/06.
[5] For the sake of brevity, we do not list all references and refer the reader to [11] for details.

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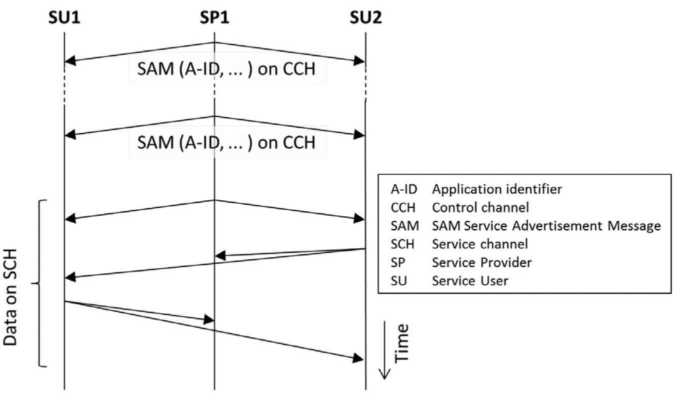

Fig. 2. Illustration of the service user / provider concept with Service Advertisement Messages (SAM) sent on the CCH and data on a SCH. Data can be transmitted from the service provider to the service user, vice versa or both directions.

important optimization metric and channel switching is typically triggered by lower-layer performance indicators (e.g., channel utilization, interference and noise levels). One relevant scenario is the envisioned communication support for vehicle platooning: when faced with the choice of supporting a stable platoon operation while having fewer number of other lower-priority services, or – as an alternative – supporting a larger number of services at the expense of platoon service interruption, the former option will take precedence. The example scenario underlines that road safety services in vehicular networks have different demands on service and communication quality than regular, non-safety networks. Also, some services that will be supported on SCHs (e.g., high-frequency periodic safety messages among vehicles in a platoon, cooperative sensing and exchange of cooperative maneuvering commands) are related to road safety and traffic efficiency, thus there is a need for prioritization of those services.

Furthermore, vehicles do not necessarily consume the same services. Instead, service usage depends on the type of applications or application sets of the vehicle, its equipment with driver assistant systems as well as user preferences. For example, one driver might prefer to consume a platooning service (i.e., join a platoon), whereas another could be more interested in receiving information about local points of interest; even if this would entail utilizing more resources than if both users were to consume a single service, if there are sufficient channel resources to support both services, an MCO scheme should allow both drivers/vehicles to consume their preferred service.

The focus on service priorities and user preferences does not imply disregarding the channel utilization. Once the application and user requirements are satisfied, the goal is to optimally allocate channel resources to support as many services as possible. To that end, another design goal of SAMCO is reducing the channel switching frequency. The channel switching process penalizes the performance in two ways: (1) during the channel switching of a non-negligible duration, the goodput is zero; and (2) each provided service that changes channel needs to notify potential users about the change by generating a service advertisement on the CCH.

In defining the MCO behavior, we make use of the service provider (SP) and service user (SU) concept (Fig. 2) In short, SP is an entity (either a vehicle or an RSU) in charge of generating service advertisements and providing the service, while SU is the user/consumer of the service. While typically the SP transmits data to the SU, some services require the opposite directions of data traffic (e.g., a probe vehicle data service, where an RSU advertises the service and vehicles generate the data). Also, a bi-directional exchange between service provider and users is possible. The latter is relevant when a service implies a reliable exchange of data between two vehicles, typically via unicast, e.g., for a make-space operation when a vehicle joins a platoon. In general, an entity can assume the SP and SU roles both concurrently and interchangeably (i.e., a vehicle providing a service would assume an SP role, and likewise it could assume an SU role once it wants to consume a service).

The SP / SU concept represents a general framework for service provisioning in a vehicular network with MCO support, which covers a broad range of services for road safety, traffic efficiency and infotainment applications. In particular, the concept also includes specific services for vehicle automation and platooning, such as cooperative sensing and the exchange of maneuvering commands (see Section 2.2).

3.1. System assumptions

We make the following system assumptions for the design of the proposed MCO algorithm.

- Vehicles and RSUs are equipped with dual transceivers: one transceiver is continuously tuned in the CCH and the second transceiver can dynamically switch between SCHs.
- Critical safety messages are transmitted on the CCH, i.e. the 'always-on-safety channel'. Stations periodically broadcast service announcement messages (SAMs) on the CCH. Their periodicity is determined by the application requirements.
- Each SAM at minimum contains an application ID to uniquely identify the service and the ITS-G5 channel on which the service is provided.
- Optionally, a SAM may contain: (i) the channel load for some or all channels (e.g., in the form of channel busy rate metric [24] or channel load information of 802.11 [1]); (ii) the frequency of messages sent by the service (by SP, SU, or both) in Hz; (iii) the message size (or message size distribution, if message size is variable); and (iv) the expected duration of the service (i.e., SP's estimate of how long it will provide the service).
- The service provider (SP) decides to select a SCH irrespective of the SUs, i.e., there is no coordination between SPs and SUs.
- The SP role takes precedence to a SU role – if a vehicle needs to provide and use services simultaneously, it will assume the SP role. Note that the SU role can also be fulfilled if the service that it needs to use is on the same channel where the same vehicle provides its service as a SP.
- Services are assigned in pre-defined, i.e. standardized, priority groups that are known to all SPs. This ensures that there is no channel hogging by a SPs that could decide all of its services have highest priority; and that future services can easily be assigned into existing priority groups.
- Service priorities on SU side (i.e., which service to consume) are based on user preference.

3.2. Algorithm for channel load estimation

For a channel switching algorithm to schedule services efficiently, the SP needs to know the availability of channel resources on each of the SCHs. However, channel load estimation for multiple channels is not trivial unless we have the same number of transceivers as there are channels. Specifically, a certain amount of time is lost when a transceiver moves from one channel to another (IEEE 1609.4 [6] defines a 4 ms guard interval for switching). Furthermore, besides channel switching, to estimate the load on the channel, the transceiver needs to stay on the channel for a certain period of time (e.g., Cisco WiFi access points spend 50 ms per channel per scanning session[6]). If the channel load estimation is performed frequently, in addition to being detrimental to goodput, in vehicular networks it can result in missing important information, due to time-critical nature of many services. For example, if a time-critical service (e.g., platooning) is running, chances for actively scanning other channels, akin to that of estimating the channel utilization in WiFi networks[7], are limited. For these reasons, we propose a new channel load estimation algorithm that uses SAMs to implicitly estimate the load on channels to which neither of the transceivers is tuned. In the remainder of the paper, we refer to this method as "SAM-based", whereas we use the term "PHY-based" for the active channel load estimation.

The algorithm for SAM-based channel load estimation assumes that every communicating node (either vehicle or RSU) continuously logs the SAMs transmitted on CCH. For each SCH, the node calculates an estimate of the channel load using a moving average of certain duration (e.g., we use 2 seconds in our simulations in Section 4), which takes into account the completeness of information provided in SAMs, since SAMs can contain different level of detail for different services (as explained in Section 3.1, beyond minimum information in SAM, which includes application ID and channel, SAM can also contain information on channel load, the frequency of messages and message size). In cases where SAMs contain incomplete information (e.g., lacking message size), the algorithm produces a probable range of channel load for each of the channels in the form of an upper and lower bound. In addition, each communicating node calculates the PHY-based channel load (using channel busy rate metric [24] or similar) for the channels it is currently on (i.e., CCH and one of the SCHs). This is done in a passive way, whereby the node does not move to a particular channel just to measure the channel load; rather, it takes the opportunity to measure the load of those channels it is already on. This approach aims at reducing the number of times a transceiver needs to switch channels and minimizes the risk of missing service data. Note that there will be inevitable misalignment between the SAM- and PHY-based channel load estimates. Possible reasons are lost SAMs, limited service-specific information in SAMs, or sudden bursts of data traffic on channels (e.g., when entering a busy intersection with a large number of vehicles), where the load will be underestimated until all the SAMs are processed. In order to alleviate the misalignment problem, we use the SAM-based estimation as an initial step in channel switching process. Specifically, before an SP decides to switch to the SCH suggested by SAM-based estimation, it will briefly switch to the channel and estimate the load using the PHY-based method. Only if the PHY-based method confirms the SAM-based estimation, the SP moves its services to the new SCH.

The accuracy of the SAM-based channel load estimation depends on the level of information details in SAMs (Section 3.1). For example, if the complete set of optional information about message size, rate, and frequency is available, the SAM-based load estimation will be more precise than with a subset. We explore this issue by setting a variable for estimate precision through simulations in Section 4.

3.3. Service provider and service user behavior

Figs. 3 and 4 show the flowchart for SP and SU.

On the provider side, the SP initially loads its service configuration and waits for requests from applications to announce and execute a service. To provide a service on a SCH, the channel selection and switching decision is based on the SAM- and PHY-based channel load estimation (Section 3.2). In a first probing step, the SP, before sending a SAM on the CCH, tunes to the "best candidate" SCH identified by SAM-based estimation, e.g. a default service channel, and measures the PHY-based load, to make sure that it is in fact a non-congested channel. Once it selects a channel, the SP will provide all of its services on this channel (i.e., it does not provide services on multiple channels concurrently) until the load on the current channel reaches a predefined threshold. When the load is high, the SP checks if it provides any of the services that are lowest priority of all on the channel, i.e., considering the services provided by other SPs. If yes, SP stops providing the lowest priority services. For all of its services the SP periodically rebroadcasts SAMs on the CCH, so that new nodes entering the range can have up-to-date information on available services and periodically estimate the SAM-based load in their vicinity. Certain services might not need to provide the service on SCH before there are SUs that want to consume the service (e.g., platoon leader might announce, but not transmit a service before there are other vehicles in vicinity willing to join the platoon). Therefore, such services might require an SU to acknowledge consumption of the service. After one SU has acknowledged the consumption through a unicast message to SP, subsequent SUs consume the service without the need for acknowledgement.

In addition to SPs, SUs can also calculate the SAM- and PHY-based load, particularly for services for which SUs generate significant data traffic the services. In such cases, an SP should aim at ensuring service continuity of service for its SUs. In particular, for platooning services, all vehicles in a platoon can piggyback the load information for each channel they have information on. While this load estimation is imperfect, it provides useful information to the SP, as it allows a platoon to cooperatively select the channel that is likely to have low load for all platoon members. However, the load on the SUs is relevant if only one service is being run by the SP; otherwise, it would be difficult to coordinate between multiple services and their associated SUs.

Note that some details are omitted from Fig. 3 for clarity. For example, if the load on the channel is lower than the maximum allowed load but not lower by more than predefined value (e.g., 5% of channel time), the SP drops one of the lowest priority services randomly. In case the load is larger than the upper limit, all lowest priority services are dropped. Similarly, SAM- and PHY-based channel load estimation (probing) are not explicitly displayed in Fig. 3; they are contained in step "Check channel load on all SCHs".

In the SU role (Fig. 4) – contrary to the SP role, where the services are categorized into priority groups – a node will load the user preferences, which list the application IDs in which the user is interested. Upon reception of a SAM, the SU moves to the channel that carries the higher priority service according to the user preference. This behavior allows the service users to select the services of their interest. In case of multiple concurrent highest priority services, if the SU was consuming one of the services, it stays with that service; alternatively, it randomly selects a service.

4. Simulations

In order to assess the performance of the proposed MCO solution, we perform simulations with a purpose-built simulator that models the channel estimation, SP, and SU behavior in a highway scenario. Since there is scarce work on performance evaluation of the channel switching in general, and it is particularly difficult to find studies analyzing the impact of channel switching solutions on the application-level performance, instead of a comparative study, we focused our simulation analysis on determining the ability of SAMCO to:

[6] Cisco Wireless LAN Controller Configuration Guide, Release 5.2: http://www.cisco.com/c/en/us/td/docs/wireless/controller/5-2/configuration/guide/Controller52CG.html.

[7] Channel utilization is defined in IEEE 802.11-2012, clause 8.4.2.30 [1].

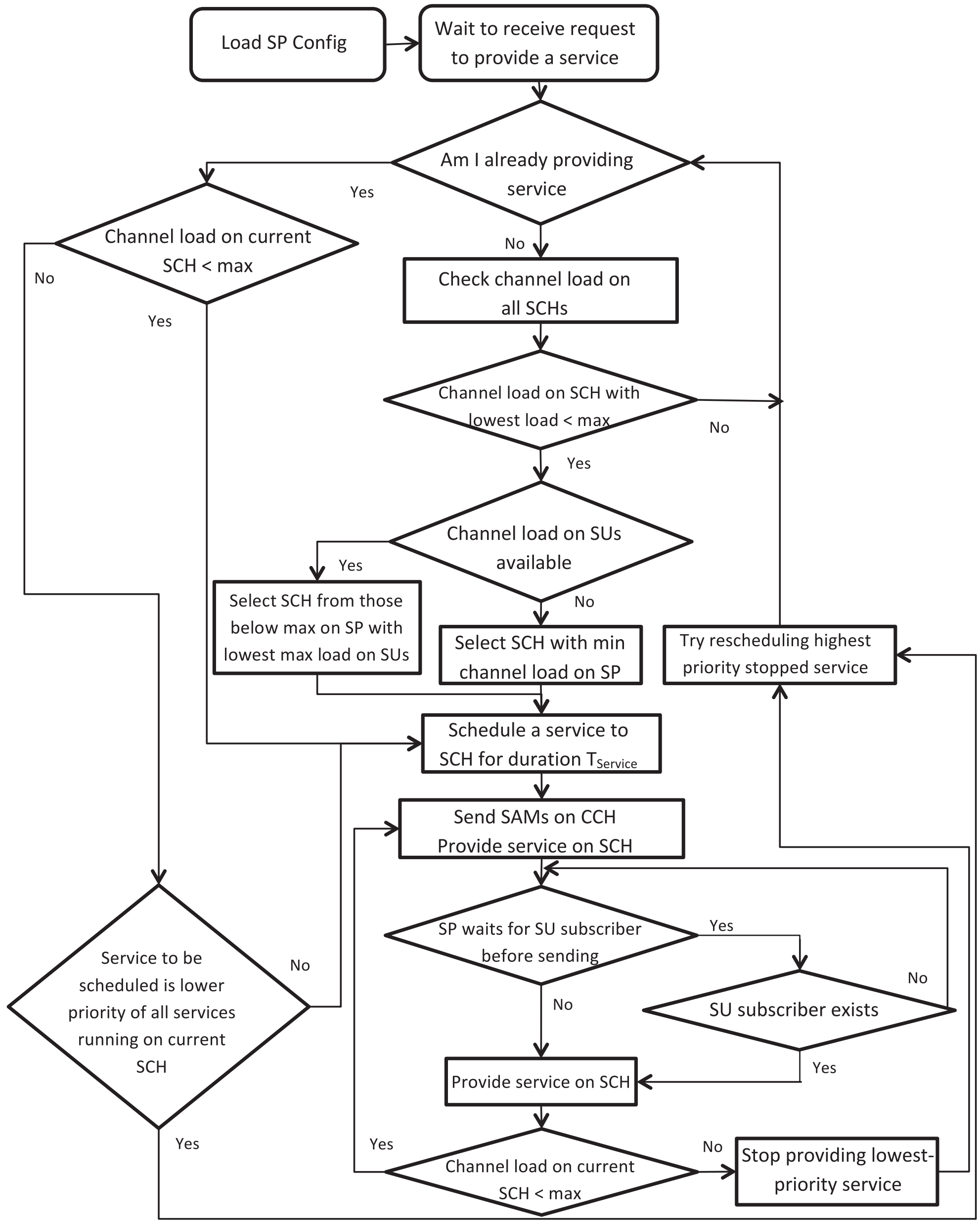

Fig. 3. Operation flowchart for multi-channel operation on Service Provider (SP) side.

1. Prioritize the services in a dynamic environment, since the ability to provide continued service for high priority services is an important design goal;
2. Minimize the frequency of channel switching in situations of high channel load;
3. Control the load on the channels by disabling the lower priority services until the channel load is acceptable;
4. Determine the capacity of ITS-G5 systems to support platooning, as a relevant example for a low-latency, high priority application.

Table 2 contains the pertinent simulation parameters. In terms of message sizes, frequencies, and the channel load allowed, we set the relevant parameters to those currently discussed in U.S. and European standardization bodies [1–3,24]. As the channel load metric, we use the Channel Busy Ratio (CBR) as defined by ETSI [24] as the proportion of time in which the detected energy level on a channel is above a predefined Clear Channel Assessment (CCA) threshold.

PHY-based channel load estimation via CBR measurements is susceptible to imperfect information and message bursts that can create a rapid variation in load reading. Furthermore, the SAM-based channel load estimation is dependent on the freshness of SAMs and the availability of optional load information. To model this variation in the simulation, we introduce "noise" into the channel load estimation as follows. For each vehicle, the model calculates the ideal PHY-based and SAM-based load. Then, for each estimate, we add a random variation of Gaussian distribution with zero mean and a configurable deviation to the ideal measurement (for the values used in simulation, see Table 2).

The mobility model is based on the simplified cellular automata model [25]. We use a one second time step and the speed distribution of vehicles distributed according to parameters in Table 2. We do not model the detailed behavior of vehicles in a platoon (e.g., distance variations, string instability, etc.), as our focus is not on platoon movement, but rather on communication aspects of MCO.

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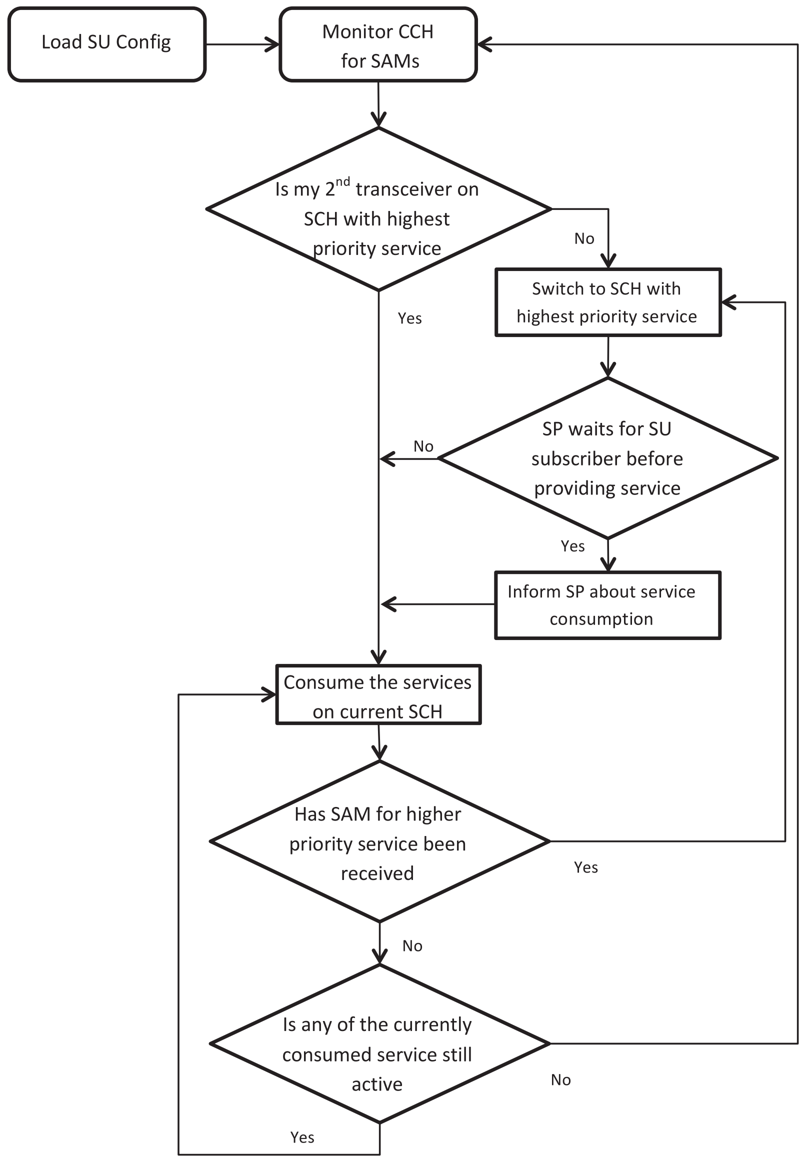


Fig. 4. Operation flowchart for multi-channel operation on Service User (SU) side.

Similar to Fig. 1, we simulate three SPs executed by RSUs at distances 2, 5, and 7 km from the beginning of highway. These RSUs represent static services that can be generated by, for example, requests from the Internet. The remaining SPs are mobile (vehicles).

To stress-test our proposed MCO solution, we define the concept of offered load as the proportion of data traffic generated by services across all SCHs. Since a 10 km long highway has multiple collision domains, we divide it into 500-meter regions and generate the offered load in each of them according to the target scenario (e.g., for a scenario with offered load of 60%, we generate enough services so that the offered load in all highway regions is as close to 60% as possible). Initially, we generate the offered load by assigning services to random vehicles and on random channels within each region to achieve target channel load; as the vehicles move, they generate different load in different highway regions. For platooning service, every SU (platoon member) generates the same amount of data as the platoon leader's SP: 20 msg/s. For other services, we restrict the data generation to SPs, therefore SUs are exclusively receivers.

We assume that, once generated, the service continues to be active until either the vehicle providing the SP exits the highway or until the service is stopped due to high channel load. To that end, we define the proportion of successfully provided services as the proportion of generated services that were uninterrupted (i.e., continuously active) from their initial generation until their termination (e.g., by vehicles providing them exiting the highway). The same principle applies for all services, with the addition in case of platoons wherein both SP (platoon leader) and SUs (platoon members) generate data traffic. Therefore, for a platoon to be successfully provided, both SP and all SUs need to be able to be able to transmit their messages uninterruptedly.

5. Results

In this section, we present and discuss the results of the simulation-based performance evaluation related to the ability of SAMCO to efficiently support service prioritization, minimize the frequency of channel switching, and control the channel load.

5.1. Supporting service prioritization

Fig. 5(a) shows the proportion of successfully provided services as the offered load on the channels increases up to the theoretical

Table 2
Simulation parameters.

Parameter	Value
Highway length & configuration	10 km, 3 lanes/direction
Number of vehicles	500–2000 (depending on scenario)
Number of platoons	30–300 (depending on scenario)
Platoon size	2–8 vehicles (uniformly distributed)
Vehicle speed (platoon & non-platoon)	25–50 m/s (uniformly distributed)
Message frequency	
∼ per vehicle in platoon	20 msg/s [21]
∼ per service (mobile, non-platoon)	5–50 msg/s (uniformly distributed)
∼ per service (static, RSU)	100 msg/s
∼ of SAMs	0.5–2 msg/s (uniformly distr)
Message size	Platoon 300 Bytes; other: 300–500 Bytes (uniformly distributed)
Service priority	Platoon: 0; other services: 1–4
Data rate	6 Mb/s [1]
Transmit power	23 dBm EIRP
Receiver sensitivity threshold	−95 dBm
CBR limit	0.6 of channel capacity [24]
CBR estimation variation (per vehicle)	PHY-based: N(0,0.03) SAM-based: N(0,0.05)
Window *t* (defining max. age of SAMs, cf. Section 3.2)	2 s
Simulation duration & runs	100 s, 10 runs per each distinct scenario

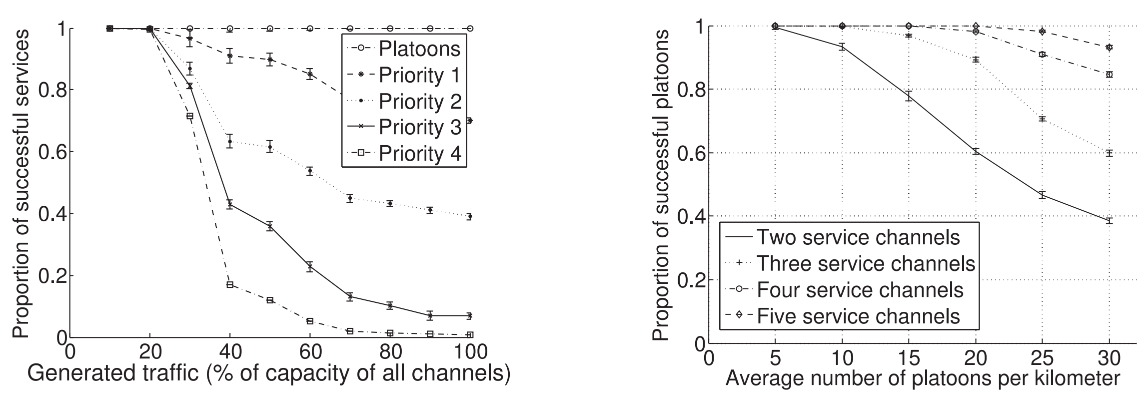
maximum of 100% channel load. When the offered load increases to 30% of the channel capacity, SAMCO reacts by stopping lower priority services. At 60% of generated load, virtually no lowest priority services (priority 4) are active; the remaining higher priority services are reduced proportionally, except for the platoons, which have the highest priority and are continuously active. The results shown in Fig. 5(a) show that SAMCO efficiently supports the service prioritization and allows for service continuity for platooning as the highest priority service. Note that the generated load differs from the actual channel load, since as the load increases, the services are stopped so that the CBR is kept below the maximum allowed value. Therefore, the actual channel load on the channels is equal or lower than the generated load.

5.2. Proportion of successfully served platoons

In the Fig. 5(a) scenario, the platoons themselves do not generate enough data traffic to congest the channel, since there are only 30 platoons in the simulation (three per kilometer). Fig. 5(b) shows a hypothetical situation where platoons would generate data traffic that creates channel congestion. The results can be interpreted as the probability that a platoon will be have enough communication resources for uninterrupted operation. The load from other applications is kept fixed at 20% of the total channel capacity. We also performed tests with no other applications except for platoons, and observed results practically equal to those in Fig. 5(b). The reason why the load from lower priority applications does not affect platoons is that SAMCO stops remaining applications until their success ratio goes to virtually zero due to the increased load from platoons.

The results indicate that two channels (SCHs) with a data rate of 6 Mb/s cannot support a high density of platoons – already with 10 platoons per kilometer, the success rate drops to 90%. The situation improves significantly with an increased number of channels; five SCHs can support up to 25 platoons/km with nearly 100% success rate. Another interesting observation from Fig. 5(b) is the fact that doubling the number of channels does not directly result in doubling the success rate of platoons. The main reason for this is the vehicle mobility: certain parts of the highway contain higher density of platoons and if the platoons generate more traffic than allowed (i.e., more than 60% of CBR per channel), some platoon services need to be stopped. This is why it is difficult to achieve 100% success rate even with five SCHs for high-density networks (e.g., 30 platoons/km).

One way to support a higher number of platoons and other services with the same number of channels is to increase the channel data rate. This would allow higher message rates on the channel at the expense of reduced effective range at which services can be



(a) Proportion of successfully provided services. Five channels with 6 Mb/s channel rate, 60% CBR max, 30 platoons and 20-200 other services with varying message rates. Error bars represent one standard deviation around the mean.

(b) Proportion of successful platoons. 6 Mb/s channel rate, 60% CBR max, 20% load from other services. Error bars represent one standard deviation around the mean.

Fig. 5. Proportion of successful services of all type (a) and platoons in particular (b).

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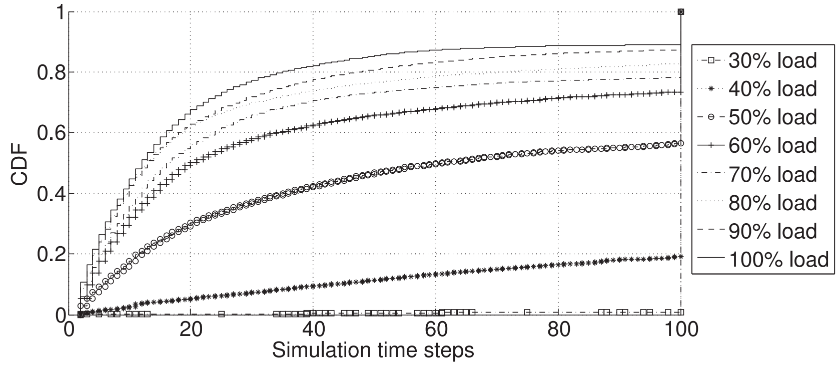

Fig. 6. Distribution of channel switching time by SPs for successfully provided services (all priority levels included) for different generated loads. Five channels with 6 Mb/s channel rate, 60% CBR max, 30 platoons and 20–200 other services with varying message rates.

offered. An alternative approach controls the transmit power, so that the available bandwidth can be used more efficiently through frequency reuse. However, the latter approach would again be to the detriment of service range.

Furthermore, these results give an indication about the ability of the ITS-G5 based vehicular communication system to support future mobility modes on highways, such as cooperative cruise control and ultimately automated vehicle operation. A large number of platoons (e.g., 30 platoons/km^2, each with 5 vehicles on average) is similar to a large number of automated vehicles coordinating for better traffic flow.

5.3. Frequency of channel switching

One of the goals of SAMCO is reducing the number of time the transceiver switches between channels. To that end, Fig. 6 shows the result of two mechanisms that a SP employs to reduce the switching frequency (also shown in SP's operation flowchart for multi-channel operation in Fig. 3): (1) it only switches the channel if the load on the channel is high; and (2) it 'bundles' several services to a single channel. Fig. 6 shows the distribution of time before the second transceiver switches from one SCH to another, i.e. the time a transceiver stays on one SCH. If the generated load is low (in this case, below 30%), there is enough channel resources for all services and there is no need to switch channels, except for the channel switching caused by a vehicle entering an area of the highway with large number of services (e.g., near RSUs). When the load on channels increases, the available channel time becomes scarce and SPs need to be more proactive in switching from one channel to another in order to provide their services. For 50% generated load, the median time that a SP spends on a single SCH is 60 time steps (seconds). Already at 60% generated load the median time reduces to 20 s, since the SPs need to switch more frequently. The reason for the shorter SSH dwell time is because the load reaches the CBR limit and also due the dynamics of the network with a large number of SPs coming in and out of each other's range. The reduction is caused by the load that reaches the CBR limit and by the dynamics of the network with a large number of SPs coming in and out of each others range. Note that, even for the scenario with 100% generated load, there are approximately 10% of services that do not change their channel at all. These are predominantly the highest priority services (platoons and priority 1 services), where the corresponding vehicles are able to travel over the highway and use the same SCH. This result indicates that SAMCO effectively forces the lower priority services to switch to another SCH in cases of high channel load and with higher priority services on the current SCH.

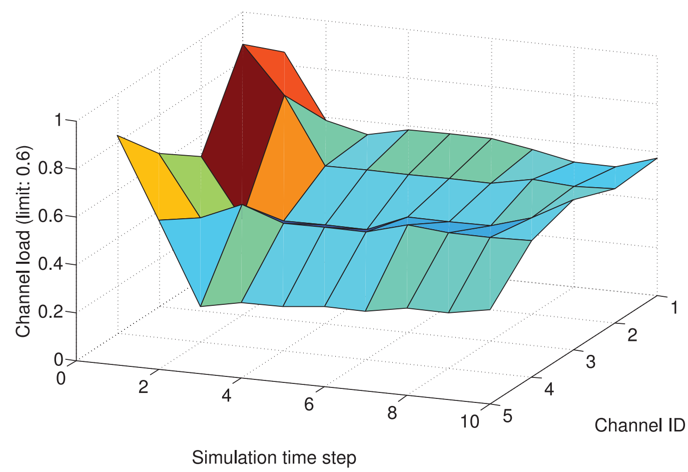

Fig. 7. Channel load behavior in the first 10 simulation steps for 100% offered load scenario measured as the average load observed on all vehicles in the first 500 m of the highway.

5.4. Behavior of channel load

Fig. 7 shows the load for all SCHs in the first 10 simulation time steps for the scenario where applications generate 100% of load supported by the channels. After some lower priority services have been disabled in the first three time steps, the load is below the 60% CBR limit. Since in high load situations SAMCO stops all lowest priority services on current channel, the load on some channels falls significantly below the limit (e.g., at time step 4). In subsequent time steps, some of the lowest priority services are then gradually restarted, thus the load on the channels starts converging to the limit. The slight variation between the channels is expected, since SAMCO favors reducing the frequency of channel switching over the perfect load distribution among channels, provided the load on the channels is below threshold. As shown in Fig. 7, SAMCO is able to help control congestion, since SPs observe the load on the channels and check priorities of services provided by other SPs; this allows SPs to determine whether any of their services is the lowest priority on the channel and thus a candidate for being stopped. In this regard, in case of high channel load, SAMCO can assist the decentralized congestion control (DCC) algorithms [24], which act as "gate-keepers" on the medium access layer, by stopping messages from lower priority services before they are transmitted on the air. While employing message prioritization, DCC algorithms most often do not distinguish message streams from specific services. If, for example, some messages from a platoon service are blocked by the gate-keeper, the platoon might need to be dismembered, thus rendering useless all messages that were sent for the platoon. SAMCO can be used to limit the influx off messages to the gate-keeper by stopping all messages from a specific application, so that these messages never even reach the gate-keeper.

6. Conclusions

We presented SAMCO, a new scheme for multi-channel operation in a decentralized network with vehicle-to-vehicle and vehicle-to-infrastructure communication for safety and traffic efficiency applications. Instead of high spectrum utilization as the primary objective, the design of SAMCO specifically addresses service priorities and user preferences. Relying on the flexible framework in the IEEE 1609.4 standard [6] and the MCO support in the architecture of the simTD field trial [7], our simulation-based study has shown that the proposed scheme effectively supports service prioritization, continuity of service for high-priority services, and graceful degradation for low-priority services.

While the initial deployment of vehicular communication systems expected in the next few years does not make use of MCO, with a growing equipment rate in vehicles and an increasing number of applications, MCO will become an important system feature. In particular, as a relevant and representative use case for automated driving, platooning has very high requirements on uninterrupted operation (same applies to other low-latency, high-reliability applications such as lane merging, C-ACC, etc. [23]). For scenarios with platooning in the presence of lower-priority services, our simulation-based performance evaluation has also given an indication about the number of platoons that can be supported in a MCO-enabled system. We have also shown that SAMCO reduces the load on the wireless channels, thereby contributing to data congestion control at the service level, and efficiently reduces the number of channel switching operations.

To enable SAMCO in the light of current standardization efforts in EU and the U.S., the main requirements are related to: (i) the information provided in service advertisements; and (ii) application prioritization. Specifically, SAMCO will yield better results the more of the optional information is contained in SAMs: (i) service channel that the node plans to use for the service, (ii) channel load information, (iii) frequency of messages sent by the service (by service provider, user, or both), (iv) message size, and (v) expected duration of the service. To that end, part of the future work is to provide input to standardization bodies on the required information fields in SAMs to enable more efficient channel switching. In terms of application priorities, SAMCO can make use of the application identifiers used in the existing standards, such as Provider Service Identifier (PS-ID) in the IEEE 1609 stack and the Application ID (A-ID) in the ETSI protocol stack.

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