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Hybrid V2X Communications: Multi-RAT as Enabler for Connected Autonomous Driving

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***Abstract*—Exploiting the full potential of automated driving systems requires reliable wireless communication enabling network connectivity and cooperation among vehicles. Multiple V2X technologies are addressing the requirements of connected autonomous driving applications. Recent investigations have shown that none of the technologies is flexible and reliable enough to serve the diverse requirements in terms of delay, reliability and throughput under the various circumstances observed by vehicles. Hybrid V2X communications enables the coordination of multiple communication technologies to efficiently adapt to the time-varying channel and road traffic conditions. Further it allows to increase reliability and throughput of transmissions by combining multiple RATs in parallel. This work gives an overview of the potential, challenges and main design aspects of hybrid V2X communications considering the latest technological developments.**

***Index Terms*—V2X, hybrid communications, multi-RAT, profile selection, diversity, connected autonomous driving**

I. INTRODUCTION

Self-driving vehicle technology and its potential to change the future of mobility has raised tremendous interest in society within recent years. Progress in research and development towards the first fully automated car (level 5) has been unexpectedly fast, and first cars reaching full automation in specific driving scenarios (level 4) are expected to be released for commercial fleet applications by end of the decade. Still, automated driving systems rely on local control and sensor-based vision systems only, which suffer from limited reaction times, vision range and the lack of cooperation between vehicles. Wireless communication is key to complement in-vehicle driving systems in order to drastically reduce reaction times, increase the vision range of ego vehicles beyond line of sight and enable cooperative maneuver planning [1]. However, current V2X technologies are neither flexible nor reliable enough to serve the diverse delay, reliability and throughput requirements of connected autonomous driving. To overcome these limitations, hybrid communications enable the coordination of multiple communications technologies in order to efficiently adapt to the requirements posed by the driving situation. Figure 1 gives an overview of application categories for Connected Autonomous Vehicles (CAVs) and currently available V2X communication options. Each category represents a different set of requirements concerning the key performance indicators delay, reliability and throughput. On the other hand, each communication option has specific capabilities and performance characteristics rendering it more or less suited to serve the different applications in certain communication and driving scenarios. A crucial challenge of hybrid V2X communications, is how to map the different applications to one or a suitable combination of multiple Radio Access Technologies (RATs) under fluctuating radio channel and network load conditions. Hybrid V2X communications have been extensively studied, often also under the term of *Heterogeneous Vehicular Communications* [2], [3]. In contrast to the sequential use of multiple RATs known from vertical handover, which has been well investigated for heterogeneous wireless networks [4], hybrid V2X relies on simultaneous use of the different technologies. So far, research has focused primarily on a complementary combination of WiFi-based IEEE 802.11p and cellular communications based on 3G [5], [6] or 4G technology [7], [8]. However, with evolving LTE-V2X (Rel. 14) technology also new non-complementary communication options with similar capabilities and performance characteristics have been introduced [9]. Due to the new communication options a smart selection becomes even more important and challenging. Consequently, hybrid approaches are currently being investigated in various projects, e.g., 5GNetMobil, 5GCAR, CONVERGE and CODECS. In this work, we would like to clarify the concept of *Hybrid V2X Communications* and to reveal its potential, the technical challenges and essential design aspects in the context of connected autonomous driving.

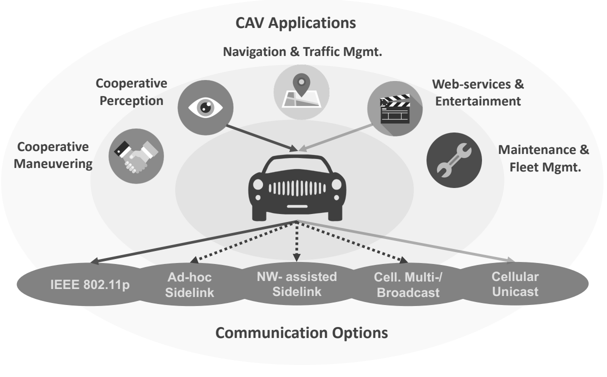

Fig. 1. CAV application categories and communication options

Therefore, the remainder of this work is structured as follows: In Section II CAV application categories with their specific challenges are introduced. Next, in Section III a State of the Art (SoA) overview of V2X technologies and profiles reflecting the communication options is given. Section IV then discusses the components of a hybrid communications system enabling the selection of communication profiles. Subsequently, Section V explains basic selection approaches, complemented by Section VI focusing on multiple profile specific aspects. Finally, in Section VII the work is concluded.

II. CONNECTED AUTONOMOUS DRIVING APPS

Enabling the vision of connected autonomous driving can be expressed in two fundamental demands: First, vehicles need to cooperate in order to increase traffic efficiency, safety and driving experience. Second, the driver should be able to spend the freed time for his personal purpose. Based on whether the communication influences the vehicle’s control systems, applications can be classified either into safety-critical or non-safety critical.

A. *Safety Critical Applications*

Safety critical use cases mainly involve cooperation among vehicles (V2V), either in an active or passive fashion. In the passive case, which we refer to as *Cooperative Perception*, vehicles mutually exchange information in order to improve the accuracy of vehicles’ perception and increase its vision range beyond line-of-sight. The information shared ranges from vehicles’ status data such as position, speed and heading, to more complex data formats containing information about tracked objects. Cooperative perception does not pose strict delay and reliability requirements since packet loss is tolerable to a certain degree. Instead, the challenge is rather to deal with the high number of messages transmitted causing channel congestion, which renders channel access for delay critical services difficult. Active cooperation, referred to as *Cooperative Maneuvering* also aims at increasing safety but further improves traffic flow and efficiency by enabling more efficient driving maneuvers compared to ego autonomous vehicles. Example use cases are high-density platooning, intersection crossing and lane merging. Due to high fuel savings achieved by short inter-vehicle distances down to $5\,\mathrm{m}$, platooning is one of the most promising use cases. However, the targeted close inter-vehicle distances pose extremely high communication requirements (transmission delay down to $5\,\mathrm{ms}$, packet reception ratio above $99.9\,\%$) to avoid vehicle collision in case of emergency braking.

B. *Non-safety Critical Applications*

Besides safety-critical also non-safety critical applications will utilize the hybrid communications system. In contrast, non-safety critical applications are mostly related to Vehicle-to-Network (V2N) communication, e.g., accessing the Internet. They have less strict delay and reliability requirements, instead the communication system has often to deal with high throughput. We differentiate following categories: the web-service and entertainment class, ranging from applications with relaxed requirements such as web-surfing or accessing Emails up to high-data rate applications such as video streaming. Further the navigation and traffic management class which is crucial since vehicles driving system is highly dependent on up-to-date lane level precision map data and road traffic information. Finally, the maintenance and fleet management class being especially interesting for vendors, transport companies and car sharing providers, which can be considered as low priority background data traffic. While most of the throughput related requirements can already be served with SoA cellular technology, the challenge is to ensure coexistence with safety-critical application (especially when utilizing the same RAT).

III. COMMUNICATION TECHNOLOGIES & PROFILES

A. *IEEE 802.11p*

In 2010 the 802.11p amendment, extending the well-established IEEE 802.11 standard for V2X communication was introduced. The Outside of Context of Basic Service Set (OCB) mode was defined allowing communication without requiring authentication/association between end nodes or with an access point. In order to increase robustness to high Doppler shifts observed in vehicular scenarios, operation in 10 MHz broad frequency channels was introduced instead of the 20 MHz used for classic WiFi. The MAC protocol operates as for classic WiFi including 802.11e extensions to introducing four priority classes. Carrier sensing and random backoff is used to reduce the probability of collisions causing packet loss. Due to the hidden node problem, carrier sensing can fail and collisions occur. Furthermore, collisions occur if multiple nodes randomly choose the same time slot for transmission. Due to unacknowledged broadcast communication packet losses cannot be detected and recovered on MAC layer. This can be solved by periodically repeating the packets at application level. As common for IEEE 802.11 WiFi, the PHY layer is not tightly coupled to the MAC layer. Currently, 802.11a OFDM PHY layers with reduced bandwidth are used but more modern once, e.g., 802.11n, 11ac or 11ax could be introduced for increased throughput and robustness.

B. *LTE-V2X*

In 2016 3GPP started the work on extensions of the LTE protocol for better support of V2X applications [10], which was concluded with LTE Rel.14 in 2017. Besides enhancements of the Uu interface used for unicast and multi-/broadcast between network and vehicles, the most prominent feature was the extension of the Device-to-Device (D2D) communication over sidelink (PC5 interface) to better support V2X communication. Additional pilot symbols were added to support relative speeds up to 250 km/h. Network-assisted sidelink (Mode 3) allows the cellular network to centrally control spectrum access on the sidelink. In ad-hoc Mode 4 vehicles autonomously decide when to access spectrum, forming a distributed radio access protocol as used in 802.11. Different than 802.11, LTE sidelink Mode 4 does not implement carrier sensing to defer from channel access in case the channel is detected to be busy. Motivation is the limited benefit due to hidden nodes and the non-deterministic delays. Instead the ad-hoc sidelink uses sensing-based

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semi-persistent scheduling, where a set of periodically repeated resources is selected based on initial sensing of the potential resource set. It is built on the assumption of regular spectrum access patterns caused by periodic message transmission of V2X applications [11]. Still, collisions can occur if spectrum access patterns change. This especially happens because vehicles move, and patterns can be different in different geographic areas. To mitigate the effect of permanently colliding if two or more vehicles choose the same resources for periodic transmissions, resources are regularly reselected. Same as for 802.11p, LTE sidelink is broadcast only. Besides relying on the application taking care of mitigating the effect of undetected packet loss by frequent retransmissions, LTE sidelink allows for blind HARQ retransmissions. Each packet is then transmitted twice which reduces the packet loss ratio but at the same time requires twice as many spectral resources. Due to its complementary modes, LTE-V2X can be considered as a hybrid technology.

C. 5G-V2X

3GPP standards beyond Release 14 are considered as 5G splitting up in two tracks: the New Radio (NR) commonly considered as 5G and further enhancements to LTE. The study for a 5G NR sidelink has started in June 2018 targeting to finish the specifications in Release 16. So far, LTE-V2X supports only fixed Transmission Time Intervals (TTI) of $1\,\mathrm{ms}$. Besides new spectrum and waveform, the 5G NR access design will enable a flexible and scalable TTI structure with intervals below $1\,\mathrm{ms}$ ($500\,\mu\mathrm{s}$ is expected) in order to reduce air interface latencies, especially for time-critical V2X applications. The reduction of TTIs will either be realized by reducing the number of symbols per TTI (short TTI) or by introducing shorter symbols (new numerologies). For a true evolution of sidelink communication the introduction of unicast communication is being discussed. This would enable the possibility for acknowledged communication significantly increasing the transmission reliability compared to current broadcast solutions. Furthermore, carrier aggregation up to 8 carriers, 64-QAM modulation and the introduction of transmit diversity schemes is currently under discussion.

D. Communication Profiles

Due to the new sidelink modes introduced by 3GPP, referring to the access technology only, e.g., LTE-V2X is no more sufficient to describe the communication options available. Especially for a hybrid system where a selection needs to be accomplished on a preferably fine level choosing the RAT only is not sufficient. Instead, the selection also needs to involve the corresponding communication modes. To overcome this limitation, we introduce the term of Communication Profile (CP). A CP is composed of the RAT plus it’s mode of operation, e.g., LTE-V2X ad-hoc sidelink (Mode 4). Further specific configurations can be associated with a CP enabling more precise adaptation to the demanded QoS requirements, e.g., by adjusting the Modulation and Coding Scheme (MCS). Figure 2 gives an overview of relevant vehicular profiles based on LTE/5G-V2X and IEEE 802.11p technologies. The profiles are grouped in two main classes differing in terms of the data traffic flow: cellular and direct. For cellular profiles the data flow is indirect, i.e. it needs to pass through the cellular network (e.g. base station). In contrast, for direct profiles the data is transmitted directly between vehicles in proximity without the need of passing through the network. Direct profiles can be further distinguished into: network-assisted and non-assisted. For the NW-assisted profiles a central network entity controls the assignment of radio resources to be used for communication between vehicles. In contrast, for the non-assisted category radio resources are accessed according to a distributed MAC protocol, e.g., CSMA/CA in 802.11p.

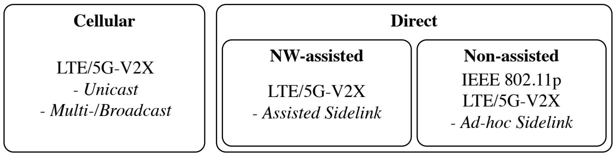

Fig. 2. Overview of communication profile categories

IV. HYBRID V2X COMMUNICATIONS

From a general perspective a hybrid communication system can be described as a set of multiple RATs being coordinated to be flexibly used for data transmission. Its purpose is to enhance the overall communication performance by combining the capabilities of the different technologies. In case of vehicular communications, the different access technologies are represented by the beforehand introduced CPs. For hybrid V2X communications the key challenge is to select appropriate profiles for each application considering the profiles’ performance characteristics. Profiles can have complementary performance characteristics (e.g., LTE-V2X unicast, 802.11p) but also similar characteristics (e.g., LTE-V2X ad-hoc sidelink, 802.11p) [12]. In vehicular networks the observed profile performance typically changes dynamically over time due to frequently changing channel states and network topologies arising from high node mobility. These changes need to be considered for the selection of the best suited profile in terms of satisfying the applications Quality of Service (QoS) requirements. Besides the decision making, also the operation of profiles is an essential part. It includes configuration, establishment and supervision of the different communication links. Instead of selecting single profiles for the data transmission, which we refer to as *Single-Profile Selection*, also multiple profiles can be selected. In case of *Multi-Profile Selection* multiple profiles are combined in order to increase reliability (profile diversity) or throughput (profile aggregation) of the communication system.

A. Example Communication Scenario

Figure 3 gives an example of hybrid V2X communications in a highway scenario with multiple applications

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$A_1, ..., A_4$ and communication profiles $CP_1, ..., CP_4$. A platoon is formed by the trucks T_1, T_2, T_3, being controlled by the platoon leader T_1. The leader uses single-profile selection to determine the best performing profile for exchanging control information within the platoon (A_2), 802.11p (CP_1) in this case. In addition, the leader selects a cellular link CP_2 to obtain supplementary information, about road traffic and coverage situation on the planned platoon track (A_1). Besides the trucks, three vehicles V_1, V_2, V_3 are placed in the scenario. Vehicle V_1 disseminates perception data in form of tracked object (A_3) towards vehicles in proximity (V_2). In order to increase the achieved throughput it equally distributes the perception data on two profiles (aggregation), using a combination of cellular multi-/broadcast (CP_4) and ad-hoc sidelink (CP_3) profiles. Furthermore, vehicle V_2 situated on cell edge needs to conduct an emergency brake (A_4). In order to reliably reach neighbor vehicles (also out of coverage), it combines two non-assisted profiles (CP_1, CP_3) for redundant transmissions (diversity) carrying the emergency brake warning message.

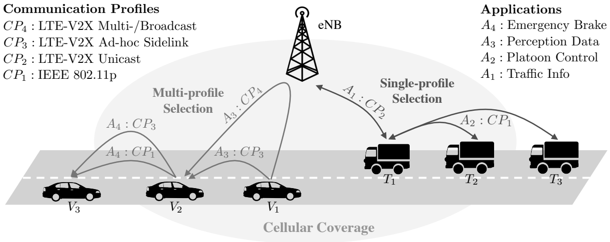

Fig. 3. Example for hybrid communications in a highway scenario

B. Protocol Architecture

The protocol architecture depicted in Figure 4 abstractly describes the hybrid communication system from a vehicle perspective, without defining a concrete system architecture based on the participating communication and selection entities. It consists of four main components: the access interfaces, the C-ITS & TCP/IP stack, the applications layer and additionally the newly introduced Hybrid Communications Management (HCM).

1) Applications Layer: On the applications layer multiple safety-/non-safety critical applications are running in parallel. Each of them has specific requirements and uses a set of standardized or proprietary message formats. To enable selection on message level the application requirements need to be mapped to the utilized messages types. This is especially important when using multiple message types, since requirements are usually expressed by the worst case and do not need to be guaranteed for each single transmission. For instance, in a platoon most of the data traffic is generated by periodic status/control messages which are required to keep the platoon stable. However, the extreme delay and reliability requirements arise from the rarely occurring emergency brake event. Consequently, a selection on message level allows to efficiently adapt the communication performance to the requirements of the driving situation. To enable message level selection the HCM needs to acquire knowledge about the message type to requirements mappings. Besides pre-defined requirements for standardized messages, each application may define own requirements for the utilized message types.

2) C-ITS & TCP/IP Stack: Below the application layer two alternative stacks are placed: First, the well known TCP/IP stack and second the C-ITS stack, a modified version of ETSI C-ITS upper layers [13]. The TCP/IP stack enables routing of application layer messages over conventional IP networks using TCP/UDP for message multiplexing. In contrast, the C-ITS stack enables generation and forwarding of V2X messages generated by the facilities layer. The facilities layer can be considered as a set of protocols providing services for the generation of V2X messages enabling application layer functionality. Most prominent examples are the periodically transmitted Cooperative Awareness Message (CAM) and the event-triggered Decentralized Environmental Notification Message (DENM). In addition, currently new message types for cooperative perception/maneuvering addressing CAV applications are being standardized. The stack is complemented by the GeoNetworking (GN) protocol enabling geographic addressing and forwarding, using the Basic Transport Protocol (BTP) similar to UDP.

3) Hybrid Communications Management (HCM): The hybrid communications management is the central component of the hybrid protocol architecture. Placed between the access interfaces and the C-ITS stack, the HCM acts as a control function taking care of selecting, configuring and supervising of the CPs. Therefore, the HCM needs to define and configure a set of candidate profiles based on all demanded application to message requirements mappings as well as available interfaces, modes and configurations. Further it determines a mapping between the contained profiles and required message types which may be static or dynamically changed based on the observed selection parameters. The decision may be obtained/assisted by a remote decision entity, e.g., the base station or surrounding vehicles. After configuration, the HCM multiplexes the network layer packets containing the messages towards the configured interfaces based on the selected mappings. This also applies to the selection of multiple profiles as discussed in Section VI. Since the messages are encapsulated either in IP or GN packets, for selection the HCM needs to obtain knowledge about contained message type and originating application. Further for the transmission of GN packets over IP based networks (e.g., for LTE-V2X unicast), the HCM needs to encapsulate them in IP packets and accordingly configure the gateway settings. Further the HCM monitors selection parameters as well as active applications in order to react to changes in achievable/required communication performance requiring a re-selection of profile mappings and configurations. Therefore, it needs to obtain cross-layer information from the access interfaces and applications.

4) Access Interfaces: On the lowest level the different access interfaces, namely 802.11p, PC5 (sidelink) and Uu (uplink/downlink) are placed. Each interface has its own independent protocol stack, which can be configured by the HCM. Especially for interfaces with multiple modes, e.g., PC5 for non-/assisted sidelink, it needs to be considered that only one mode can be configured at a time. Further, the reconfiguration overhead in terms of delay needs to be taken into account (especially for profiles requiring configuration and/or resource assignments via a network entity).

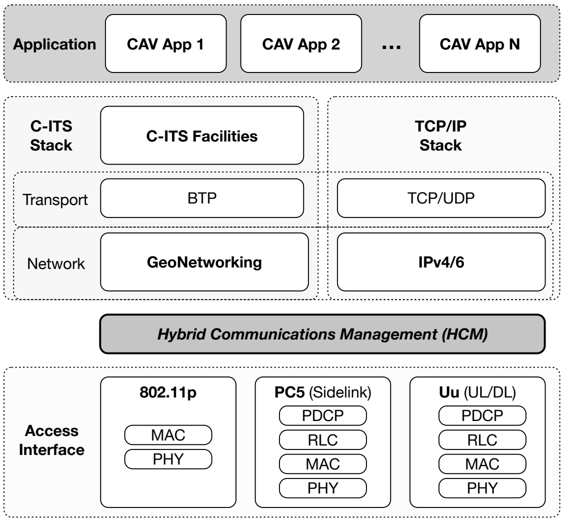

Fig. 4. Protocol architecture for hybrid V2X communications

V. Communication Profile Selection

A. Static Selection

For static selection profiles are selected based on fixed mappings between messages types, their requirements and available profiles. The mappings may be dependent on thresholds taking into account the profiles performance characteristics, e.g., for distance between source and destination. Defining the mappings is crucial since they highly influence the achievable. They can be obtained analytically, by simulations or in testbeds. Static selection is most suited for complementary profiles with fundamentally different performance characteristics (e.g., 802.11p, LTE). Typical selection scenarios are:

1) V2V vs. V2N Communication: Autonomous vehicles require to be simultaneously connected to the network (V2N) while communicating with surrounding vehicles (V2V). Static mappings can be used to map message types to profiles based on their intended receiver location (V2V - direct, V2N - cellular). Still, in case of V2V communication among vehicles not being in close proximity, instead of using multi-hop forwarding over direct technologies V2V communication over cellular links can be considered. Therefore, the static mapping could be represented by a distance threshold.

2) Safety vs. Non-Safety Critical Applications: Static selection can further be applied to guarantee coexistence between safety and non-safety critical applications. For both classes dedicated communication interfaces are assigned to avoid interference between them.

B. Dynamic Selection

The optimal profile choice is dependent on channel quality/load which makes a fixed mapping ineffective in many cases. Especially for non-complementary profiles (e.g., 802.11p, ad-hoc sidelink) with similar performance characteristics, static selection leads to suboptimal results. Instead, dynamic selection considering the observed radio and road traffic conditions can be applied in order to maximize the achieved communication performance. Dynamic selection tries to cope with performance fluctuations which are especially high in vehicular communication environments due to fast moving nodes and constantly changing network topologies. Based on the available selection parameters reflecting the current situation, the best suited communication profile can be determined. Besides deciding based on instantaneous parameters only, also predictive selection approaches considering long-term performance behavior, e.g., based on knowledge about semi-persistent resource assignments, can be applied. The decision making of selecting profiles can either be accomplished in decentralized fashion by the vehicles or in centralized fashion by a network entity. Decentralized approaches can be further divided in: distributed and autonomous decision making. In case of distributed decision making vehicles exchange control information to enable coordination of decisions. In contrast autonomous selection is based on a ego vehicle decision only. The selection approach is dependent on the network coverage as well as desired optimization goals. Decision making can be accomplished/assisted by the network for vehicles in-coverage only, out-of-coverage vehicles need to rely on decentralized decision making approaches. Following optimization goals can be considered:

1) Network-centric: Network-centric optimization aims at network-wide performance optimization, e.g., load balancing. As depicted in Figure 5 all vehicles $V_1, ..., V_I$ and their respective applications $A_1, ..., A_J$ are considered for the decision. It can be realized by centralized or decentralized distributed decision making.

2) Vehicle-centric: For vehicle-centric optimization the goal is to maximize the communication performance for a single vehicle's V_j applications $A_1, ..., A_J$. It is mostly suited for decentralized, autonomous selection.

3) Group-centric: A vehicle group is formed based on a common application A_j, e.g., platooning. The selection aims at maximizing the performance for all vehicles $V_1, ..., V_I$ in respect to A_j. Besides centralized and decentralized distributed selection approaches, also autonomous selection may be considered, e.g., platoon leader selects profiles for communication in the platoon.

Based on the desired optimization goal a selection approach (centralized/decentralized) can be chosen and accordingly, a system architecture be defined. The choice of selection entities, e.g., vehicle, base station, road side unit, is crucial since it implies the availability of selection parameters and the required signaling overhead.

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Exchanging selection parameters introduces additional signaling overhead in terms of radio resources and delay, which poses a trade off to the obtained gain in selection performance. For instance, vehicles know about utilization of unlicensed and the base station about licensed resources. In case selection and control entities, e.g., base station, are separated, signaling overhead arises from the interface configuration and resource assignment procedures, e.g., vehicles autonomously selecting cellular profiles need to request radio resources before transmission.

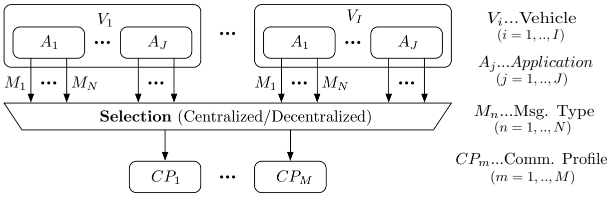


Fig. 5. System model for communication profile selection

C. Selection Parameters

Optimal profile choices require a set of selection parameters accurately reflecting the achievable communication performance. The set can vary among different profiles which renders the selection challenging. Following categories of parameters should be considered:

1) Radio Access Parameters: Radio access parameters are obtained from the access interfaces and often unique. We differentiate: *Radio Link Quality Parameters* reflecting the wireless channel quality and *Radio Resource Usage Parameters* as indicator for the current channel load. Link quality parameters are primarily used for cellular unicast communication to describe the quality of wireless links. Examples are the Reference Signal Received Power (RSRP) or the derived Reference Signal Received Quality (RSRQ) in LTE. For direct technologies no link quality parameters are available at the sender since receivers cannot provide feedback for broadcast communication. Instead, the radio resource usage parameters measuring the channel load which reflects the channel access probability/delay play an important role. Typically used is the Channel Busy Ratio (CBR) measuring the average time a channel is occupied with transmissions. Further also for NW-controlled/assisted profiles information about resource availability such as the Radio Resource Utilization (RRU) counting the average number of allocated resource blocks can be used as a measure for congestion within the network.

2) C-ITS Parameters: Using radio access parameters only, may not result in optimal profile choices. Due to their high dependency on the road traffic situation, especially for vehicles using direct technologies the decision quality can be increased when involving C-ITS parameters. Information about position, speed and heading encoded in V2X messages and beacons received from neighboring vehicles can be collected to obtain further parameters reflecting the road traffic conditions. Examples are: number of surrounding nodes, average distance to neighbors, heading-/speed differences and time since last reception. As observed road traffic conditions are correlated to the channel load, C-ITS parameters can be used to predict changes in communication performance.

3) Vehicle Control Parameters: In addition to parameters obtained from the communication system, vehicle control and local sensor data can be utilized. Most simply, the speed of a vehicle can be interpreted as a criteria on how fast channel conditions may change. For autonomous vehicles further detailed knowledge about planned trajectories, driving scenarios and the vehicles environment is available. While trajectories allow a long term prediction of channel conditions especially on network level, information on driving scenarios and environment conditions may enable prediction of large-scale fading effects, e.g., caused by buildings.

VI. MULTI-PROFILE SELECTION

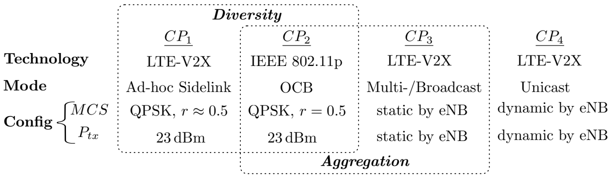
In case the selection of a single profile cannot guarantee the demanded QoS requirements, Multi-Profile Selection (MPS), combining multiple communication profiles, can be applied in order to increase throughput or reliability of the hybrid communication system. From the decision making perspective MPS can be considered as an extension of the selection principles introduced in the previous section. Two cases can be differentiated:

A. Profile Aggregation

For Profile Aggregation (PA), two or more profiles are selected for parallel transmission of non-redundant data in order to increase the transmission capacity. The aggregation of profiles allows to increase the available bandwidth per user, and hence the achieved throughput. Furthermore, it can reduce the access delay by load balancing, especially for non-assisted direct technologies which are highly dependent on the observed channel load. Instead of transmitting all packets over a single profile, they are distributed by the HCM towards the selected profiles for independent transmission. The distribution can either be accomplished equally or the split ratio can be dynamically adapted based on the observed profile state, e.g., buffer status and achieved throughput. PA is suitable for scenarios with stable channel conditions showing low outage probability.

B. Profile Diversity

In contrast to PA relying on non-redundant transmissions, Profile Diversity (PD) applies redundant transmissions to increase the achievable reliability. Making use of multiple wireless links by transmitting the same data over different profiles, enables time, space (different sending times and positions due to different queue and processing delays) and frequency (other bands) diversity. This increases robustness against packet loss on individual links, reducing the outage probability respectively. On receiver side the Packet Selection (PS) diversity scheme can be applied. For PS the HCM accepts the first successfully decoded packet and discards duplicates subsequently received. As a consequence, at least one packet needs to be successfully decoded. More sophisticated schemes based on additional coding applied by the HCM on receiver side can enable reconstruction of packets at the receiver even in case all received packets are corrupted. Further PD can cope with different equipment of vehicles, e.g., receiver equipped with 802.11p or LTE-V2X only. It needs to be considered that the redundant use of profiles reduces the spectral efficiency of the hybrid system, which may lead to channel congestion and a degradation of the system performance.



		CP_1	CP_2	CP_3	CP_4
Technology		LTE-V2X	IEEE 802.11p	LTE-V2X	LTE-V2X
Mode		Ad-hoc Sidelink	OCB	Multi-/Broadcast	Unicast
Config	MCS	QPSK, $r \approx 0.5$	QPSK, $r = 0.5$	static by eNB	dynamic by eNB
	P_{tx}	23 dBm	23 dBm	static by eNB	dynamic by eNB

Fig. 6. Example set of profiles for Multi-Profile Selection

C. Example Profile Combinations

Figure 6 shows an example set of four active candidate communication profiles $CP_1, ..., CP_4$ composed of RAT, CP and specific configurations to be combined. The direct profiles CP_1, CP_2 are configured by the HCM with commonly used, similar parameters: QPSK modulation with a code rate of approximately 0.5 and the maximum allowed transmit power of 23 dBm. In contrast the cellular profiles are configured by the base station, for multi-/broadcast (CP_3) statically dependent on the required reception area and for unicast dynamically based on the observed channel quality. For V2V applications demanding high throughput, e.g., cooperative perception, the profiles, CP_3 and CP_4 can be aggregated. Therefore, the data traffic is split to be equally distributed using both profiles. Furthermore, for safety-critical V2V applications such as cooperative maneuvering demanding highly reliable message delivery the direct profiles CP_1, CP_2 can be operated redundantly. Instead of transmitting the packets once, the HCM duplicates and distributes them to both profiles for independent transmission.

VII. CONCLUSION

In the future automated driving systems will become highly dependent on vehicular communication technology. However, CAV applications ranging from mission critical maneuver negotiation to conventional entertainment services are challenging the communication system with demanding and diverse QoS requirements. Since SoA technologies such as 802.11p or LTE-V2X are not able to guarantee the diverse requirements under the various driving and communication scenarios observed by autonomous vehicles, multiple technologies need to be simultaneously used. Hybrid V2X communications enables Multi-RAT coordination in order to efficiently adapt to the observed situation by selecting the best suited technologies based on the application requirements. Due to the introduction of multiple communication modes in LTE-V2X, instead of selecting RATs only, the selection of communication profiles, further defining a communication mode, is necessary. The selection of appropriate communication profiles is crucial to the achievable performance of a hybrid communication system and can involve one or a combination of multiple profiles. In both cases the principles are similar: in order to flexibly react to the highly dynamic vehicular environment, communication profiles need to be dynamically chosen based on the observed channel and road traffic conditions. In case even choosing the best suited communication profile cannot guarantee the demanded requirements, multiple profiles can either be aggregated for increased throughput or be redundantly operated for increased transmission reliability. Besides showing the main design aspects, this work leaves open to define a selection architecture and algorithms. However, independent from a concrete realization hybrid V2X communications will become a key component enabling the vision of connected autonomous driving.

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