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Car-to-X Communication: System Architecture and Applications

Modern vehicles include a multitude of highly sophisticated technologies for providing active safety. Driver assistance systems like *Adaptive Cruise Control (ACC)*, *Active Braking*, *Night Vision* or *Pedestrian Recognition* are only some examples, which are devoted to enhancing future road safety. Basically, all these systems rely their actions on information received from their local sensors, which are primarily Sonar, Radar, Lidar, or Camera. For detecting vehicles in the direct proximity, *Park Assistant Systems* use ultrasonic sensors, which possess a limited measurement range about 4 m. For detection of more distant vehicles or pedestrians, camera-based object detection algorithms are deployed. With today's automotive cameras, a reliable detection can be achieved up to a total distance of 80 m. In contrast, Long-range Radar or Lidar possess very promising transmission ranges up to 200 m, which enables, e.g., active braking even at high speeds. Compared to Radar, a Lidar-based system can also be deployed to detect heavy rain or snowfall, which delivers valuable input for dynamically calibrating the sensitivity threshold of the *Electronic Stability Control (ESC)* or *Traction Control System (TCS)*.

Nevertheless, these sensors generally monitor only the direct proximity of a vehicle, and do not share their collected information with other vehicles. Thus, sensing is restricted to the line of sight, leaving out hidden and unrecognized but possibly relevant vehicles or other obstacles. Furthermore, since Radar and Lidar are still expensive, car manufacturers are expected to offer this sort of safety technology only to buyers of luxury cars in the near future.

The Car-to-X technology offers new possibilities for enhancing active safety and traffic efficiency at a large scale. In Figure 2.1 the extended driver horizon by means of Car-to-X, in comparison to the limited range of local sensors is visualized. Using C2X communication, warnings of potential risky situations are no longer limited to local detection only. Instead, a dangerous situation is detected once and then forwarded via several hops, such that approaching vehicle drivers may react in time and adapt their driving behavior accordingly.

C2X communication is based on the IEEE 802.11p standard and enables time critical safety applications at very low data transmission delay. In this context, the European Commission has initiated the allocation of the 30 MHz spectrum, from 5.875 to 5.905 GHz exclusively

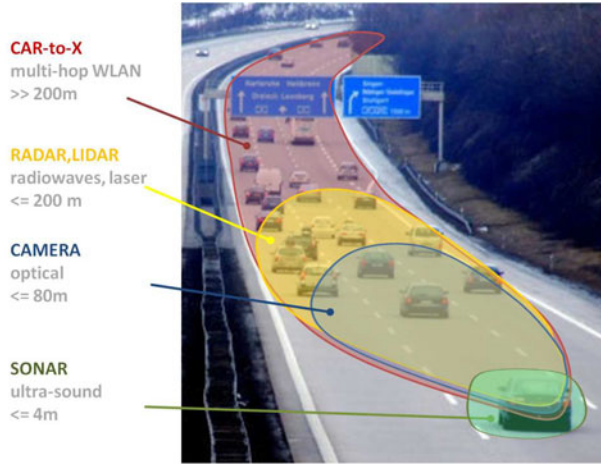


Figure 2.1: Vehicle sensor range comparison

for safety-related communications. Currently developed chipsets allow communications between stations in ad-hoc mode without the necessity of a permanent infrastructure connection. According to the European profile [25] of 802.11p, three channels with 10 MHz each, are assigned. More details on the physical layer properties will be given in Chapter 6.

In the following section the underlying system architecture of the Car-to-X technology is presented exemplarily by means of the architecture developed within the German field operational trial sim^{TD} [26], which is considered to be very close to the ETSI ITS reference architecture [2] and the communication scenario as envisioned by the C2C-CC [27]. The architecture is described in terms of involved components and communication between them. The presented system has been designed within work package WP 2.1 of the sim^{TD} project [8]. As a leading member of this work package, the author of this thesis has made substantial contributions to the design of the overall architecture [28], [8], [9], [29], [11], [30], [7].

In the second part of this chapter the C2X message types and routing algorithms as specified by sim^{TD} and the ETSI standardization body are outlined. Subsequently, the general benefits of Car-to-X applications for road safety, traffic efficiency and driver convenience are discussed.

2.1 C2X System Architecture

In the recent 20 years a significant reduction of road fatalities of almost 50% inside the European Union has been observed [31]. To a great degree this is due to the introduction of strict road safety policies defined by the European Commission Road Safety. Among others, these policies include a harmonization of penalties in the member states as well as a tightening of laws regarding working conditions of vehicles and drivers. Besides regulatory measures, several major technical achievements in the area of passive and active safety have decreased the consequences of accidents or even avoided them in the first place.

However, despite this promising trend, the evolution stills lacks behind the ambitious targets of the European Commission Road Safety. Whereas the first white paper of the European commission in 2001 had its main focus on safety and security of transport [32], in the latest white paper from 2010, sustainability has grown further in importance. Accordingly, by the year 2050 a reduction of 60% of carbon emission on the roads is aspired [33]. On a technical level, cooperative Intelligent Transport Systems (ITS) networks based on C2X communication are considered as a key technology to achieve the next major breakthrough towards a strong improvement of active safety (see Section 2.2.1) and traffic efficiency (see Section 2.2.2).

In the German research project sim^{TD} [26],[30] the Car-to-X communication is shifting from a pure research topic towards a first deployment of such a system. In sim^{TD} partners from the automotive domain, the telecommunication domain, the federal state government, several universities and research institutes have gathered to validate technologies and applications for C2X communication in a setup that is representative for a realistic deployment scenario. For that purpose about 120 controlled vehicles with hired drivers are responsible for creating certain traffic situations where applications may be tested and validated. About 100 RSUs and two traffic authorities are involved to forward messages between the different ITS domains. The traffic centers are mainly responsible for smoothing the traffic flow and reducing the traffic congestion as much as possible.

2.1.1 Components and Communication Channels

The comprehensive and seamless networking of vehicles and infrastructure represents a significant technological and organizational challenge. The sim^{TD} architecture as presented by *Stübing et al.* [30] is complex, as many different protocols and data formats are required and many stakeholders are involved. Figure 2.2 shows the system architecture from the perspective of the different components and domains as well as their interactions. In general, the system architecture is composed of two domains. In particular, these are the

- *Vehicle domain*, which comprises the hardware and software for the vehicular subsystem, and the
- *Infrastructure domain*, comprising the subsystems relevant for the infrastructure services.

The vehicles themselves are able to communicate with each other using dedicated short range communication technology based on IEEE 802.11p. Therefore, they are equipped with so-called *ITS vehicle stations (IVS)*, which deploy the ITS applications on respective hardware. The sim^{TD} scenario further includes RSUs, which are also integrated in the vehicular network and, thus, are able to communicate with an IVS. A RSU can be connected to traffic light switches in order to control traffic signs in urban scenarios. Moreover, the RSUs are connected to the infrastructure domain in order to provide connectivity from vehicles to backend services.

Besides 802.11p ad-hoc communication, as a key technology, vehicles are equipped with cellular communication hardware in order to have IP-based access to backend services and to route safety-related messages over long distances. If available, vehicles may use IEEE 802.11b/g for IP based connections via hotspots in inner city scenarios.

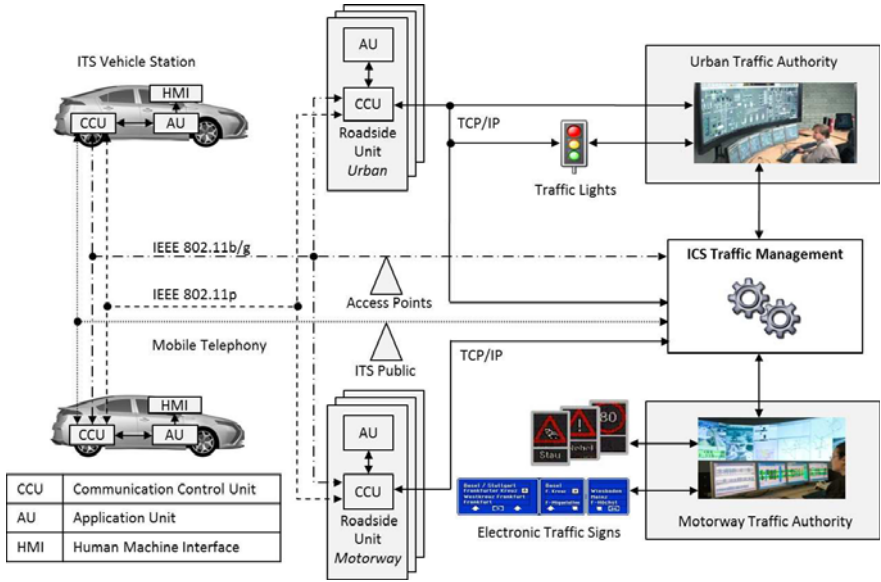


Figure 2.2: Car-to-X system architecture and communication links

A C2X system architecture, like the one deployed in sim^{TD} , may include different *ITS Central Stations (ICS)*, each responsible for a different type of road network. For instance, in sim^{TD} the *Hessian State Office for Road and Traffic Affairs* takes care of the motorways and rural roads whereas the *City of Frankfurt* covers the urban road network inside the test area.

Communication paths in sim^{TD} are vulnerable towards various attacks against security and driver's privacy. In order to prevent corruptive messages to sabotage the network, all transmitted messages have to pass various security checks. This also includes functionalities to impede tracking of vehicles in sim^{TD} . A detailed description of the entire C2X security architecture will be given in Section 3.5.3.

An IVS is comprised of the *Communication Control Unit (CCU)* and the *Application Unit (AU)*. The components implemented on the CCU handle all communication from the physical up to the network layer. This includes the implementation of respective sender/receiver modules for each communication channel, as well as techniques for channel access and congestion control on top of it. Applications that require low latency are also running on the CCU. Beside the data derived from external communication, the CCU also provides the AU with internal vehicle data observed via the *CAN (Controller Area Network)* bus. The vehicle AU hosts the C2X applications, outlined in Section 2.2.

2.1.2 Forwarding Types

Besides message generation and evaluation, the timely and directed distribution of information represents an important aspect of vehicular networks. The previously described system

architecture interconnects vehicles and infrastructure to a comprehensive communication network, where information may be routed between several instances over long distances. Forwarding of C2X messages has been described in [27], [34] and successfully implemented in sim^{TD} [35]. In the following the basic forwarding types are recalled:

- **Unicast:** Unicast messages are sent from one sender node to exactly one predefined receiver node. Depending on the distance, the message is either transmitted directly, or forwarded via multiple hops. Typically this type of addressing is used for C2I communication between vehicles and RSUs.
- **Topologically-Scoped Broadcast (TSB):** The Topologically-Scoped Broadcast represents a special type of flooding algorithm, where the sender limits the dissipation scope by defining a *Time-To-Live (TTL)* counter. For most implementations like in sim^{TD} the TTL is defined as a maximum hop count, which is decremented by every forwarder before the message is broadcasted again [35]. Experiences from previous FOTs yielded that this type of forwarding may lead to congestion very quickly and therefore should be used very rarely.
- **Single-Hop Broadcast (SHB):** For Single-Hop Broadcast the TTL value is set to one, which limits the distribution of messages to the direct neighborhood. For most safety applications, which do not require multi hop, this represents the preferred addressing type.
- **Geographically-Scoped Broadcast (GBC):** The so called *geocast* is the appropriate addressing type, in case messages are associated to a geographical validity. Geographical regions may be either defined as a circular area given a center point A and radius r . Or, the region is defined by a rectangular area, given two points A and B and a height value h . If the vehicle is located outside the dissemination area the message is forwarded via *directed flooding*. Hence, always the node closest to the defined area is broadcasting the message. Having reached the destination area, the message is distributed using TSB.

For forwarding of message between vehicles, every vehicle maintains a *Neighborhood Table*, which is built upon frequently sent CAM messages and includes the mobility status of all vehicles in direct communication stage. It should be noted that forwarding algorithms are not restricted to the vehicular ad-hoc domain, only. If available, a vehicle may also use a cellular link or any other infrastructure-based communication to forward the message to its destination.

2.1.3 Message Types

For safety and traffic efficiency related information exchange as well as for service announcements, the ETSI ITS standardization group has specified respective message sets. In Figure 2.3 the general C2X message format is illustrated. Besides the application payload, further information for network and facility layer is attached to every message. On network layer the sender ID, position, speed and heading are included, together with the current timestamp. In the following the tuple, consisting of position, speed and heading is denoted as *mobility data*. For forwarding of messages, addressing details and a geographical region are attached. On facility layer, additional information for evaluating and prefiltering of messages is added. For instance, by indicating the event type (CauseCode), messages can

C2X Network Header		C2X Message Payload	
Network Layer Data		Facility Layer Data	
		Generic Information	Concrete Message Information
Sender's ID, position, speed, direction, timestamp etc.	Addressing details for distribution and forwarding algorithms	CauseCode, ActionId, cancellationFlag, generationTime, validityDuration	- Cooperative Awareness Message (CAM) - Decentralized Environment Notification Message (DENM)

Figure 2.3: General C2X message format

easily be associated to respective applications. Furthermore, the actionID is added for referencing different subsequent messages to the same event. Parameters for generation time and validity duration are necessary to manage the message storage on the vehicle.

The previous data fields are all common for different message types. In the following a brief description of the individual message types is given. A more detailed specification can be found in [36], [37], [35] and [38].:

- **Cooperative Awareness Message (CAM):** Using CAMs, surrounding vehicles are informed about the host vehicle's presence. The term *host vehicle* is used in this thesis to denote the reference vehicle. These messages are used to build up the Neighborhood Table and posses a generic structure. For each ITS station, i.e., basic vehicle, emergency vehicle, public transport vehicle, or RSU, an obligatory profile is chosen. This includes a list of tagged values like, e.g., vehicle type, dimensions, status of exterior lights and acceleration with respective confidence values. Depending on the situation also further safety parameters like crash status or emergency braking signals are transmitted. The list of optional tagged values is still under discussion and includes, e.g., the number of occupants or the current door status.
- **Decentralized Environment Notification Message (DENM):** DENMs are event based messages. Data elements for *content type* and *subtype* allow a fine grained addressing of respective applications. For DENMs, a destination area and location reference can be specified. The destination area is relevant for forwarding via GBC. The location reference refers to the geographical validity of the hazard and is defined as a circle, rectangle or as a trace, which consists of waypoints leading to the respective traffic situation.
- **Signal Phase And Timing Message (SPAT):** In order to enable optimized flow control on traffic light intersections, RSUs frequently broadcast the remaining green light phase for each lane. SPAT data may be further combined with messages describing the topology of the intersection for more precise referencing.
- **Service Announcement Message (SAM):** Services offered by RSUs are broadcasted via SAMs. The exact specification of SAMs is currently still an active work item of the ETSI standardization group. Note that these messages are not saftety-related and consequently, will be sent on channels other than the three channels allocated in the G5A band (see Section 6.2.1 for further details on the channel allocation).

2.2 Car-to-X Applications and Use Cases

With respect to the customers benefits, the wide range of different Car-to-X applications and use cases may be grouped into three major categories: *road safety-related*, *traffic efficiency-oriented* and *service-oriented*. In recent years, field operational trials have specified, implemented and examined almost the entire spectrum of applications [39], [40], [41]. Based on the obtained results from these projects, ETSI had consolidated the different views and then defined the *Basic Set of Applications (BSA)* [42]. Each application and use case has been selected with respect to a set of criteria, including economical, organizational, and legal requirements. Due to its near-series alignment the BSA is taken as reference in this thesis. In the following a brief summary of functionality and benefits of each use case is given, including the respective communication type and involved messages according to the specifications given in [39], [40], [41].

2.2.1 Cooperative Road Safety

In this work, a special focus is set on safety-related applications, since these are considered as the main driving force for the deployment of the Car-to-X technology. Assuming a sufficient penetration rate of C2X-equipped vehicles and infrastructure these applications possess a great potential for reducing road fatalities and damages caused by traffic accidents. According to the author's opinion, during a first deployment phase, the driver will be assisted by advisory information, given by means of optical, acoustical or haptic warnings via the vehicle's *HMI (Human Machine Interface)*. Gradually, the technology will become more mature as the data reliability and trustworthiness is enhanced, and the vehicle will automatically intervene and initiate an automatic braking or evasive maneuver to avoid upcoming accidents.

Use Case	Description	Comm. Message						
		Type	Type					
		C2C	C2I	I2C	CAM	DENM	SPAT	SAM
Emergency Vehicle Warning	CAMs include data fields for indicating a 'Siren in Use' and 'Light Bar In Use' [36], which are set by emergency vehicles to receive prioritized flow control at traffic lights. Other vehicles determine the trajectory of the emergency vehicle and inform the driver about its position and driving direction. DENMs are forwarded to inform vehicles outside the direct communication range.							

Use Case	Description	Comm. Message Type						
		C2C	C2I	I2C	CAM	DENM	SPAT	SAM
Slow Vehicle Indication	Based on frequently sent mobility data, the host vehicle continuously determines the relative distance and velocity to the vehicle driving ahead. Depending on the remaining <i>Time-to-Collision (TTC)</i> , the driver is warned.							
Intersection Collision Warning (ICW)	By monitoring the kinematic status of all vehicles entering an intersection, future paths are predicted and drivers are warned of imminent lateral collisions.							
Motorcycle Approaching Indication	A large number of accidents involving motorcycles happen at intersections with other vehicles. As vulnerable users, motorcyclists benefit from frequently sent CAMs, which are used to directly warn vehicle drivers of an approaching motorcycle.							
Emergency Electronic Brake Lights (EEBL)	By observing the deceleration, speed and brake signals, via the local CAN bus, a sharp braking is detected and a DENM is propagated. On the receiver side, the relevance is checked and a warning is given.							
Wrong Way Driving Warning	RSUs, located on one way streets or motorway exits monitor passing vehicles via CAMs to detect wrong way drivers. Upon detection, the wrong way driver as well as affected vehicles are warned via DENMs.							
Stationary Vehicle	A post crash notification or car break down warning is distributed via DENMs and includes sensor information, necessary for other vehicles to assess the situation.							

Use Case	Description	Comm. Message						
		Type	Type	Type	Type	Type	Type	Type
		C2C	C2I	I2C	CAM	DENM	SPAT	SAM
Traffic Condition Warning	If, for a certain road type, the host vehicle's speed is decreasing below a given threshold, a traffic jam is detected, and a DENM is propagated. On infrastructure side this information is aggregated and resent to the vehicles inside the relevant area. Note that for traffic jam detection, recent FOTs [26] take into account additional traffic parameters, like, e.g., the vehicle density or the relative speed between vehicles.							
Signal Violation Warning	CAMs of oncoming vehicles are observed by RSUs at traffic lights in order to detect signal violations and to warn drivers.							
Roadwork Warning	Mobile RSUs inform passing vehicles about a roadwork and related information.							
Collision Risk Warning	CAMs allow a precise assessment of the mobility of surrounding vehicles, which enables various different lateral and longitudinal collision avoidance applications							
Decentralized Floating Car Data	While traveling along the road, vehicles are collecting data via their local sensors, to detect events like, e.g., slippery roads, fog, heavy rain or a traffic jam. In case of a hazard, the affected geographical region is distributed via DENMs. Collected Probes are sent as <i>Probe Vehicle Data (PVD)</i> via RSUs to an ITS central station, which accumulates the data. RSUs announce this service via SAMs.							

Table 2.1: Application class Active Road Safety

2.2.2 Cooperative Traffic Efficiency

Car-to-X communication offers new possibilities for traffic assessment and control. Conventional traffic assessment on highways or traffic light intersections is often done by using inductor loops for detecting the vehicle density in certain areas. This technology is not only cost intensive, but it is also limited in its application. In contrast, monitoring the traffic flow via frequently sent CAM messages is far less complex and more scalable. C2I Projects like DIAMANT have shown that with a C2X penetration rate of 5 out of 1.000 vehicles a traffic jam may be determined accurately enough [43]. On the other hand, the Car-to-X technology also enhances traffic control opportunities for road authorities. Today, road authorities rely only upon variable traffic sign bridges or TMC (Traffic Message Channel) for delivering traffic and travel information to the driver. Using the C2X technology, individualized information and warnings may be directly given to each driver via the vehicle’s HMI.

Use Case	Description	Comm. Message					
		Type	Type				
		C2C	C2I	I2C	CAM	DENM	SPAT
Green Light Optimal Speed Advisory (GLOSA)	Using frequently broadcasted SPAT messages, vehicles may adapt their driving behavior at traffic light intersections. By doing so, unnecessary stops or accelerations are reduced and thus, less carbon is emitted.						
Traffic Information & Enhanced Route Guidance	Traffic information including potential traffic jams or hazards is aggregated on infrastructure side and then relayed via local RSUs. Vehicles equipped with navigation systems may take this information into account for calculating an optimized route.						
In-vehicle Signage	C2X-equipped traffic signs on the road side broadcast contextual traffic information like, e.g., speed limits, stop signs, or pedestrian crossings. By showing this information directly on a vehicle’s HMI, visibility is enhanced and warnings may be given to the driver if a traffic sign is violated.						

Table 2.2: Application class Cooperative Traffic Efficiency

Multilayered Security and Privacy Protection in Car-to-X
Networks

Solutions from Application down to Physical Layer

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