

2. Car-to-X Communication

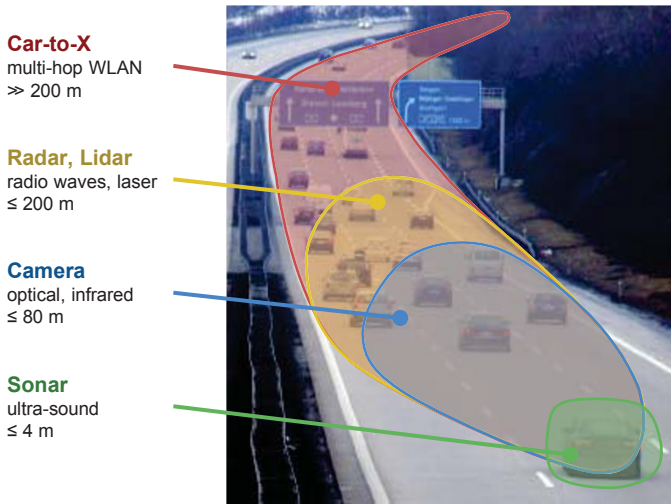
Modern vehicles carry a large number of highly sophisticated sensors to provide a various set of comfort and active safety technologies. Hence, not restricted to upper class vehicles, there are, e. g., radar or lidar sensors to enable *Active Cruise Control* or *Active Braking*, one or even multiple cameras for *Road Sign Assistance*, *Pedestrian Recognition*, or *Lane Keeping Assistance*, as well as sonar sensors for *Blind Spot Warning* or *Parking Assistance*.

All these sensors provide measured data to applications running on the vehicle. Consequently, combining all available information, a precise assumption of the local environment around the vehicle is gathered, but limited to the respective range of the respective sensor. Sonar sensors detect objects in the direct surrounding of the vehicle, i. e., in a range of up to 4 meters. Typical automotive cameras available today, provide reliable detection up to a total distance of 80 meters. Finally, credible object detection with radar or lidar systems is achievable for a maximum distance of about 200 meters, if objects are in direct line of sight.

The major idea behind Car-to-X communication is to share local vehicle sensor data with other, potentially far away, vehicles by using wireless communication. Hence, by using multi-hop schemes, whereas vehicles forward received messages, information may be transmitted over several kilometers. Thus, the view on the local environment can be expanded significantly. Additionally, since information may be forwarded by intermediate vehicles, there is no need of a direct line of sight to achieve information about an object of interest. In Figure 2.1 different measurement ranges of selected vehicle sensors are depicted in comparison and complemented by the possible additional range of a C2X communication system.

The wide range of different C2X applications and use-cases is grouped by the *European Telecommunications Standards Institute* (ETSI) into three major categories [ETSI09], i. e.,

- Cooperative Road Safety,
- Cooperative Traffic Efficiency, and



cf. [SJ10]

FIGURE 2.1.: Comparison of selected vehicle sensors with respect to utilized technologies and their respective maximum working range.

- Cooperative Local Services and Global Internet Services.

In recent years, within multiple research projects with field operational trials, e. g., DIAMANT, aktiv [AKTIV], sim^{TD} [SIMTD], or DRIVE C2X [DRIVE], almost the entire spectrum of applications was specified, implemented, and examined. Based on gained experiences, ETSI consolidated C2X applications and defined functional requirements for a *Basic Set of Applications* [ETSI10b].

Beside the weather related use-cases which are within the focus of this thesis, these use-cases include, e. g.,

- the *Intersection Collision Warning* to avoid collisions with crossing traffic,
- the *Emergency Vehicle Warning* to notify about operating rescue or police vehicles, such that the driver may make room for them,
- the *Emergency Electronic Brake Lights* emphasizing hard braking vehicles in the front,
- the *Traffic Light Optimal Speed Advisory* suggesting optimal speed to pass traffic light series at a *green-wave*,
- the *In-vehicle Signage*, informing about current traffic rules, e. g., speed limitations, and notifying once they are violated, or
- the *Traffic Condition Warning* notifying about, e. g., an upcoming traffic congestion.

Additional use-cases, like a notification about crossing trains [JF14], are under investigation and development.

Within the following sections, a short overview on the C2X communication architecture, communication technology, selected C2X messages formats, as well as area and coordinate representation facilitating such advanced applications is provided.

2.1. Overall Car-to-X System Architecture Overview

Within Car-to-X communication vehicles exchange information between each other. In addition, stations placed along the roadside are exploited to enhance communication range and to connect infrastructure-based entities to the vehicles. Accordingly, a C2X communication system architecture consist of three different basic entity types [ETSI13a] as follows.

Vehicles are equipped with *Vehicle ITS Station (VIS)* to facilitate C2X communication. The VIS thereby consists out of a computation unit⁸ hosting *applications* and *system components*. While applications are realizing C2X use-cases, system components are providing basic services required by other system components or applications, e. g., the vehicle's position and sensor data or message en- and decoding.

This computation unit is connected to an interface to the driver, e. g., a display with touch-screen, to enable interaction between the C2X system and the driver. This way, e. g., warning messages are displayed or driver input is gathered.

However, the unit additionally is connected to vehicle's internal data and local sensors. This is usually a connection to the vehicle's CAN bus. Thus, vehicle dynamics, local sensor data, vehicle state, and diagnostic data, e. g., vehicle speed, exterior lights state, wipers activation, occupied seats, etc., are available within the C2X system. Moreover, this includes a position provider, e. g., a GPS receiver, providing the vehicle's position and a reliable time synchronization source.

And finally, at least one C2X communication capable antenna, i. e.. at a frequency of 5.9 GHz, is connected to the computation unit. Hence, sending and receiving of C2X messages is facilitated.

Thereby, the communication range of individual VIS is enlarged by the mechanism of *multi-hop*. Hence, C2X messages are forwarded, i. e., received and retransmitted, by multiple stations until they reach their destination.

⁸ In fact, within research projects usually multiple interconnected units are exploited for technical reasons. However, omitting technical details, these units might be regarded as one logical entity.

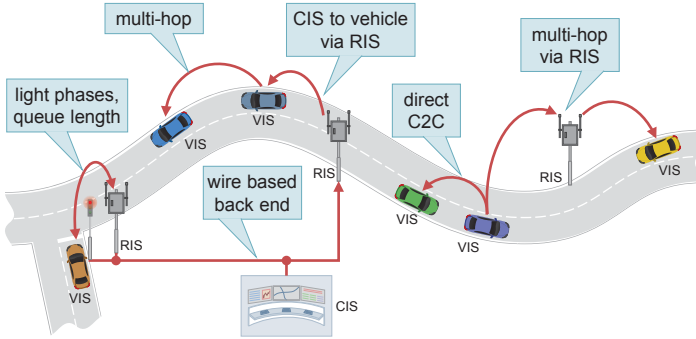


FIGURE 2.2.: The three different C2X station types, i. e., VIS, RIS, and CIS, and selected communication scenarios between them.

In addition to vehicles, *Roadside ITS Stations* (RIS), which are placed along the roadside, are involved in C2X communication. These stationary stations might further enlarge the communication range, especially within poor frequented areas, by repeating received messages.

Roadside stations might belong to a large network of stations, connected via a wire-based back-end, or are attached to one or a small group of infrastructure components, e. g., traffic lights. This way, messages might be forwarded wire-based to adjacent RIS or a station might provide an interface to infrastructure components, thus, e. g., traffic light phases are providing to vehicles or waiting queue length is communicating to a traffic lights controller.

Obviously, these roadside stations do not require an interface to a driver or a connection to vehicles data. In contrast, they are connected to the infrastructure component or the interconnection network.

As a third participating type of entities, a various set of different infrastructure-based service providers and agencies, like local traffic centers, may be connected to the C2X system. Such *Central ITS Stations* (CIS) usually do not communicate directly to road participants. Instead, they are connected to a RIS or a network of multiple RIS, which again serve as an interface between infrastructure and vehicles.

These different station types⁹ and selected communication links between them are illustrated in Figure 2.2.

⁹ Additional *Personal ITS Stations*, as, e. g., investigated within the research project AMULETT [AMU], are intended, but are not further regarded in context of this thesis.

2.2. Frequency and Channel Allocation

Car-to-X communication is based on a wireless ad-hoc network between vehicles and other road traffic relevant participants. Such a wireless *Vehicular Ad-Hoc Network* (VANET) is exploited to exchange information between these participants and to enable a large set of road safety and traffic efficiency related applications.

To enable communication for such cooperative *Intelligent Transport Systems* (ITS), carrier frequencies in the range of 5.9 GHz are allocated on physical layer. Such a technology is specified as *IEEE 802.11p* in [IEEE10] and, based on this, standardized in [ETSI12] within the European Union. Accordingly, there are eight communication channels in four bands provided to ITS communication stations. Only three bands, i. e., ITS-5GA, ITS-5GB, and ITS-5GD, are intended for C2X communication systems as in the scope of this thesis. While ITS-5GD is reserved for future use, ITS-5GA is restricted to road safety related applications only and ITS-5GB is intended for traffic efficiency purposes, respectively.

The three regarded ITS-5G bands are divided into several channels of 10 MHz width. One physical channel is allocated to be the *control channel* (CCH) while the others are defined as *service channels* (SCH), i. e., channel SCH1 to SCH6.

In order to avoid interferences between individual channels and neighbored frequency bands, for each channel the per MHz power density is limited to -10 dBm, 13 dBm, or 23 dBm, i. e., 0.1 mW, 20 mW, or 200 mW, respectively.

The channel and G5-band frequency allocation, respective power density limits, and intended purpose are depicted in Figure 2.3

2.3. Car-to-X Messages

Car-to-X communication implies information exchange between different ITS stations, i. e., Vehicle ITS Stations, Roadside ITS Stations, and Central ITS Stations. Relevant information is wrapped in *C2X Messages* and transmitted by means of wireless communication.

There are three major message formats used in multiple C2X use-cases. Firstly, the periodically sent *Cooperative Awareness Message* (CAM) as specified in [ETSI11b]. Secondly, the event-driven *Decentralized Environmental Notification Message* (DENM) as specified in [ETSI13c]. And thirdly, the *Probe Vehicle Data Message* (PVDM) containing collected sensor measurements.

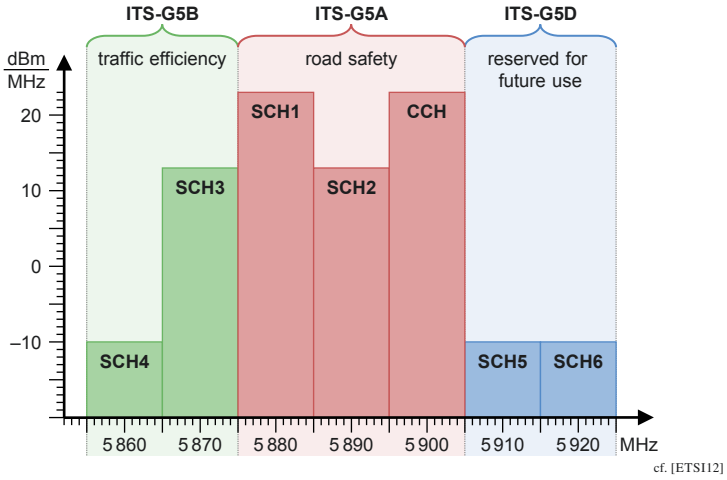


FIGURE 2.3.: Allocated frequencies for ITS channels and G5-bands, their intended purpose, and power density limits. cf. [ETSI112]

In addition, supplementary use-case specific messages are used, e. g., the *Signal Phase and Timing Message* (SPAT) wrapping information about traffic light phases, the *Road Topology Message* (TOPO) containing detailed information about the local road structure, the *In-Vehicle Information Message* (IVI) informing about local traffic signs, or the *Service Announcement Message* (SAM) sent by RISs to notify about their provided services. However, these Messages are not involved in the Weather Hazard Warning application and, hence, not further detailed.

In the following sections the three major message formats are detailed. Subsequently, a short overview on message distribution algorithms is stated.

2.3.1. Cooperative Awareness Message

The *Cooperative Awareness Message* (CAM) is the basic message in Car-to-X communication. It facilitates multiple C2X use-cases, e. g., *Emergency Vehicle Warning*, *Slow Vehicle Indication*, *Intersection Collision Warning*, or *Motorcycle Approaching Indication*. CAMs contain basic information about the current ITS station's position and state. Due to the mobility within C2X communication, CAMs are updated periodically. This way, other road participant are notified about the presence of the originating *Vehicle ITS Station* or *Roadside ITS Station*.¹⁰

These notifications are relevant to all ITS stations in the direct neighborhood.

¹⁰ Obviously, the state of a roadside stations may basically consist out of the stations position, only. Hence, the description of CAMs focuses on messages sent by vehicles.

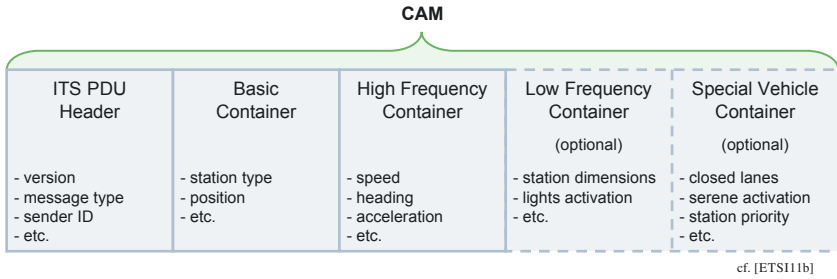


FIGURE 2.4.: General structure of the *Cooperative Awareness Message*, assembled out of the common ITS header followed by the mandatory and the optional containers.

Thereby, *single-hop* communication is applied, while forwarding mechanisms are not regarded. Hence, CAMs are broadcasted to every station in direct communication range, only.

According to [ETSI11b], as every other ITS message, CAMs contain the common *ITS PDU Header*, providing basic information about the message type, the version, etc. The mandatory *Basic Container* indicates the type of the ITS station, i. e., VIS or RIS, and the geographical position.

In case of a vehicle station, additional containers are added. The mandatory *High Frequency Container* contains all rapidly changing vehicle state data, e. g., speed and heading. They are updated within every CAM. Slowly changing or static vehicle state data, e. g., exterior light activation, open doors, and vehicle dimensions, do not have to be updated frequently. Consequently, the optional *Low Frequency Container*, wrapping these data elements, is not transmitted in every CAM. Special vehicle types, e. g., public transport, road works, or operating emergency vehicles, may add a respective *Special Vehicle Container*, containing according additional vehicle specific state information.

In Figure 2.4 this general structure of a CAM is summarized. A detailed description of the *Cooperative Awareness Message* is given in [ETSI11b].

As mentioned, CAMs are updated and sent periodically. During field operational tests, different static frequencies, i. e., 1 Hz, 2 Hz, or 10 Hz are implemented and evaluated. However, since CAMs are intended to notify about the state of an ITS station, a new CAM must only be generated if the state has changed significantly. Hence, multiple criteria are specified whenever such a significant change is indicated [ETSI11b]. Accordingly, Table 2.1 summarizes vehicle state data elements and respective thresholds. These criteria are evaluated periodically and if one condition is met, a new CAM is triggered. Thereby, a minimum time interval t_{min} of

Data Element	Threshold
heading	$\geq 4^\circ$
position	≥ 4 m
speed	≥ 0.5 m/s

TABLE 2.1.: Summary of vehicle state data elements and respective thresholds, according to the dynamic CAM generation frequency.

$$t_{min} = 100 \text{ ms} \quad (2.1)$$

between two consecutive messages, whereas CAM generation is omitted, is considered. Analogous, a maximum time interval t_{max} of

$$t_{max} = 1000 \text{ ms} \quad (2.2)$$

between two consecutive messages is considered. Thereupon, a new CAM is generated anyway.

Accessorily, the current channel load is regarded to encourage *Decentralized Congestion Control* (DCC). Hence, the minimum CAM transmission interval t_{min} may be increased if required by DCC. Such a dynamic CAM frequency facilitates as much CAM updates as needed to enable effective C2C use-cases and prevents flooding the channel with redundant information.

2.3.2. Decentralized Environmental Notification Message

The *Decentralized Environmental Notification Message* (DENM) is one of the most important messages in Car-to-X communication. It facilitates multiple C2X use-cases, e. g., *Road Works Warning*, *Emergency Electronic Brake Light*, *Traffic Jam Ahead Warning*, or *Weather Hazard Warning*. Thereby, a DENM contains detailed information about a specific dangerous situation¹¹. Hence, road participants are informed timely about relevant hazardous events in the near environment. These explicit situation notifications may be generated from roadside stations located close to the situation, e. g., at a static or mobile road works place, from vehicles detecting the danger while driving nearby, or from central stations receiving data from external sources or other ITS stations.

A timely notification of affected vehicles requires communication over large distances. Since C2X communication technologies facilitate direct transmission over

¹¹ Within respective European standardization, no sharp distinction between the terms *event* and *situation* is made. In contrast, within context of this thesis, a single notification, as reported by a DENM, is denoted as *situation*, whereas the overall real world incident is denoted as *event*. Consequently, respective terms are adapted, accordingly.

Event	Cause Code	Sub-cause Type	Description
Dense Fog	018	001	visibility reduced – due to fog
Heavy Rain	019	001	precipitation – heavy rain
Heavy Snowfall	019	002	precipitation – heavy snowfall
Slippery Road	006	005	slippery road – ice on road
Aquaplaning	007	000	aquaplaning – <i>no sub-cause</i>
Strong Winds	017	001	extreme weather – strong winds

TABLE 2.2.: Summary of *Cause Codes* and *Sub-cause Type* exploited to encode weather events within DENMs generated by the Weather Hazard Warning application.

up to several hundred meters, only, *multi-hop* techniques are applied to distribute DENMs [C2C07]. Accordingly, messages are repeated by multiple receiving stations. Thereby, no specific destination address is provided. In contrast, *geocast* mechanisms are applied, whereas geographical destination areas are consulted, instead [MAI04]. This way, messages are forwarded towards the geographical destination area (*Store & Forward*) or, if already located inside the intended region, are kept available until the end of their validity duration (*Keep-alive Forwarding*).

According to [ETSI13c], as every other ITS message, DENMs contain the common *ITS PDU Header*, providing basic information about the message type, the version, etc. The mandatory *Management Container* contains essential situation information, e. g., an *ActionID* to refer to the situation, a *validity duration* specifying how long the message is repeated, a *transmission interval* defining how frequently the message is repeated, etc.

Detailed situation specific information is wrapped within the optional *Situation Container*. This includes, e. g., the situation type, the information quality, the situation position, etc.

Thereby, situation types are encoded according to *Transport Protocol Experts Group – Traffic Event Compact* (TPEG-TEC). Hence, [ETSI13b] specifies *Cause Codes* with *Sub-cause Type* based upon [ISO13]¹². A listing of Cause Codes with Sub-cause Type exploited by the Weather Hazard Warning application is summarized in Table 2.2.

The mentioned information quality denotes the reliability of the provided information. This reliability value is given as a certain level within the range of 0 to a

¹² Earlier versions of [ETSI13c] recommend cause codes according to [TPEG06]. This is updated during international and technologies overlapping harmonization efforts.

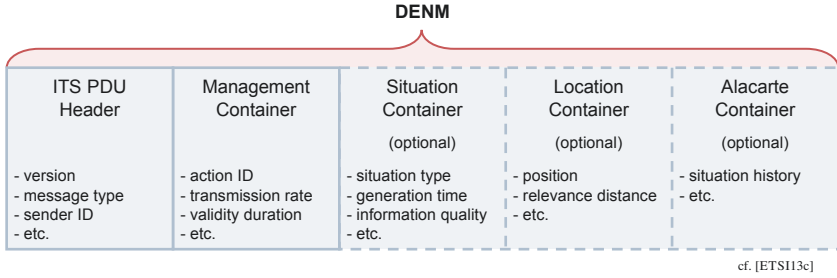


FIGURE 2.5.: General structure of the *Decentralized Environmental Notification Message*, assembled out of the common ITS header followed by the mandatory and the optional containers.

use-case specific maximum level. To determine the position of the situation, a geographical position in combination with a relevance distance is consulted, according to [ETSI13b]¹³.

The optional *Location Container* holds supplementing localization information, especially for moving situations, e. g., situation speed, situation position heading, etc. Finally, the *Alacarte Container* provides various optional additional use-case specific information, not included in other DENM containers.

In Figure 2.5 this general structure of a DENM is summarized. A detailed description of the *Decentralized Environmental Notification Message* is given in [ETSI13c].

For weather events it has to be considered that they are almost static and that a weather event affects an area regardless of which direction a vehicle approaches. Hence, no event mobility information or approaching traces are required in weather related DENMs. Based on the provided possibility to encode a geographical area, the Weather Hazard Warning expresses situations as a rectangle surrounding the hazardous area.

Since DENMs contain detailed information about local dangers, they facilitate data exchange between vehicles and from infrastructure-based services to vehicles. Thus, a DENM might be exploited to overcome the first and the second information gap as stated in Section 1.1.

¹³ Only predefined relevance distances of, e. g., 100 m, 500 m, 1000 m, or 5000 m are selectable. This implies insufficient possibility to specify a geographical region. Earlier versions of [ETSI13c] provide the possibility to define a geographical event position, according to [ETSI10c]. Thereby, the area may be shaped as a circle, a rectangle, or an ellipse as further detailed in Section 2.5.1. Current standardization efforts tending to provide these advanced positioning themes, again.

2.3.3. Probe Vehicle Data Message

By providing essential data gathered by local vehicle sensors, the *Probe Vehicle Data Message* (PVDM) facilitates multiple C2X use-cases, e. g., *Road Works Information*, *Enhanced Route Guidance and Navigation*, *Traffic Condition Warning*, or *Weather Hazard Warning*. Thereby, use-case specific relevant vehicle sensor data, like vehicle speed and outside temperature, are gathered and stored locally in combination with positioning and timing information. Subsequently, accumulated batches of these data are packed in messages and sent from the vehicle via RISs to Central ITS Stations. These *profiles* extend the data basis of the respective infrastructure-based C2X use-case or application. Thus, vehicles are exploited as mobile sensors along the road, providing essential information. Especially the infrastructure-based parts of the Weather Hazard Warning application benefit from the availability of this additional knowledge. Thus, generation of more precise warning messages is facilitated.

Since PVDMs contain rarely processed data, the information need to be interpreted. Due to rather low processing power within vehicles, this extensive data evaluation is not performed on-board, but on the infrastructure side, only. Consequently, PVDMs are not intended to be transmitted to other vehicles, but are forwarded to the CIS, instead.

Suchlike messages are based upon [ISO09] and have been exploited within large scale field operational tests as, e. g., sim^{TD} [SIMTD09j]. However, standardization is still not finalized. Accordingly, a substantiate structure for PVDMs is proposed, by the author of this thesis, which is in compliance to the container-based specification of CAM and DENM.

As every other ITS message, PVDMs shall contain the common *ITS PDU Header*, providing basic information about the message type, the version, etc. Subsequently, a mandatory *Timing and Positioning Container* containing essential position and time information for each measuring point, like geographical position, generation time, and validity duration.

Accessorily, at least one optional use-case specific container is added. Data elements included in such a container depends on the respective C2X use-case. Hence, e. g., a *Traffic Data Container* wrapping, e. g., vehicle speed and heading, or a *Weather Data Container* wrapping, e. g., ambient temperature or rain intensity, may be consulted. In Figure 2.6 this proposed possible general structure of a PVDM is summarized.

As mentioned, probe vehicle data are intended to be sent to central stations, only.

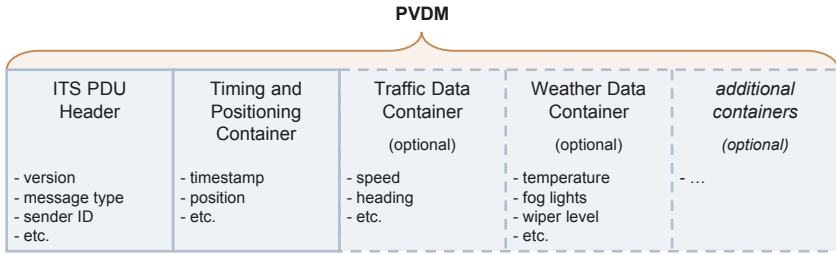


FIGURE 2.6.: Presumably general structure of the *Probe Vehicle Data Message*, assembled out of the common ITS header followed by the mandatory and the optional containers.

Thereby, roadside stations are exploited as gateways between the wireless C2X communication and the wire-based connected infrastructure side. Consequently, once a vehicle reaches the communication range of a RIS, gathered measurements are packed into a PVDM and delivered to the forwarding roadside station.

However, a RIS may not be capable to forward every use-case specific container to an appropriate CIS. Hence, they may broadcast a *Service Announcement Message* (SAM) [ETSI14] containing detailed information about their facility to receive and forward data. Thus, passing vehicles are notified about which containers may be transmitted with the current PVDM towards the respective RIS.

Such a PVDM facilitates data exchange from vehicles to the infrastructure. Thus, by exploiting PVDMs the third information gap as stated in Section 1.1 might be addressed and reduced.

2.3.4. Message Distribution Algorithms

This section provides a short introduction to message distribution in C2X communication. Respective mechanism and algorithms are mentioned and briefly outlined. Detailed information may be achieved within relevant literature and standards.

Geocast Distribution Schemes

Within Car-to-X communication messages are transmitted wireless. In contrast to conventional networking schemes, in addition to sending a message to a specified receiver by its address, i. e., *unicast*, and sending to every receiver within communication range, i. e., *broadcast*, sending messages to a specified geographical area, i. e., *geocast*, is supported [C2C07], too. Within a geocast, a message may be forwarded by multiple *nodes* to a geographical region and delivered to receivers

within that region [ETSI10d]. However, even for unicasts C2X specific conditions especially regarding the high mobility of the ad-hoc network have to be considered. Hence, each node, i. e., a Roadside or a Vehicle ITS Station, maintains a *Location Table*, storing the position, identifier, and time information of each known node. Thus, if a message from an unknown node is received, a new entry is added to the Location Table. Otherwise, if a new message from a known node is received, respective position and time information are updated. In contrast, if no message from an individual node was received for a certain time period, the node's entry is removed from the Location Table.

On the other hand, each C2X message contains respective destination and transmitting information such as

- a target destination node's *identifier* and *position*,
- a target *destination area*, i. e., a geographical region,
- a *validity duration*, determining for how long the message shall be sent or forwarded, or
- a *hop-limit*, i. e., the maximum allowed number of intermediate forwarding nodes.

Based on the intended transmission scheme, not every of the enumerated information is required.

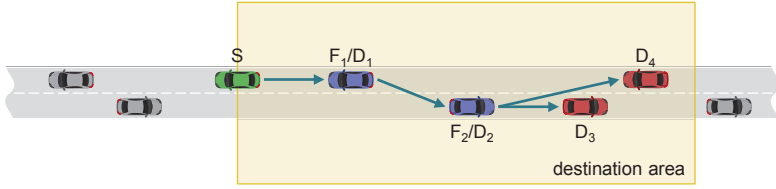
Accordingly, on reception of a message, the receiving ITS station evaluates the message's addressing and transmitting information and determines

1. if it is a destination for the message and
2. if the message shall be forwarded.

Thereby, the receiving node may be a destination due to its identifier or its location. On the other hand, if the node is a destination or if not, the message may be required to be forwarded. Thus, a node may be a destination and a forwarder at the same time. Thereby, it is considered, if the hop limit is reached or the validity duration is expired. Additionally, based on the location table, it is evaluated if there are possible receivers within communication range or if there is a route, from the current node to the destination. However, a survey of possible geocast routing protocols is given by [MA104] whereas an in-depth description for C2X communication is detailed in [ETSI11c].

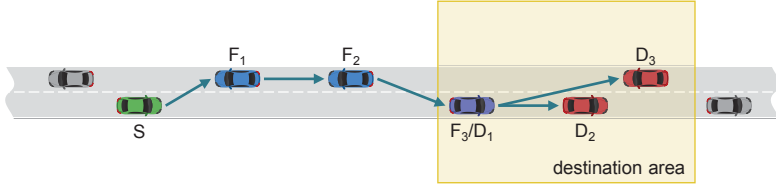
For C2X communication the following message distribution schemes are taken into account:

First of all, the *geographically-scoped broadcast*, which is commonly intended by referring to *geocast*. It is supposed to transmit information, i. e., a C2X message,



cf. [C2C07]

FIGURE 2.7.: A C2X communication scenario based on the *geographically-scoped broadcast* scheme. The source node S is transmitting a message to all nodes D_j within a specific geographical destination area. This may include multiple intermediate nodes F_i inside the area.



cf. [C2C07]

FIGURE 2.8.: A C2X communication scenario based on the *geographically-scoped broadcast* scheme. The originating source node S is located outside the destination area. Thus, the message is forwarded by multiple intermediate nodes F_i , before it is distribute to all nodes D_j within the destination area.

from a single source station to all stations within a specific destination area. Thereby, the destination area is a geographical region such as detailed in Section 2.5.1. Hence, each ITS station within the destination area, except the source itself, is a destination. Additionally, receiving nodes may forward the message within the destination area. Such a communication scenario is depicted in Figure 2.7.

In addition to distribution requirements, receiving nodes may also retransmit the message within the destination area as long as its validity duration is not expired. This *Keep-Alive Forwarding* (KAF) is intended to ensure message transmission over longer time-scale. Hence, even vehicles entering the destination area later on will receive the message, too, as long as it is valid.

Within a geographically-scoped broadcast, the source node does not necessarily need to be insight the destination area. Hence, the message is forwarded from the source node to the destination area by intermediate forwarding stations. Finally, it is distributed within the destination area, as depicted in Figure 2.8.

Local dangers, such as, e. g., objects on the road or operating emergency vehicles, are of interest within a specific geographical region. Hence, within C2X communi-

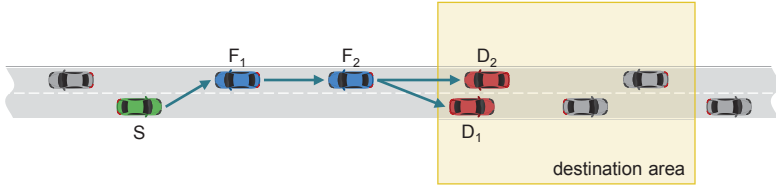


FIGURE 2.9.: A C2X communication scenario based on the *geographically-scoped anycast* scheme. A message is transmitted via multiple intermediate forwarding nodes F_i to any destination nodes D_j inside the destination area and direct communication range of the last forwarding station.

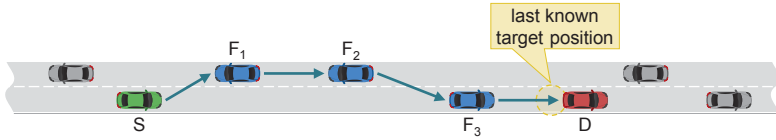
cation the geographically-scoped broadcast scheme is usually applied on DENMs, regarding these local dangers. Such as the DENMs regarded by the Weather Hazard Warning.

A variation of the geographically-scoped broadcast is the *geographically-scoped anycast*. Thereby, the message may be forwarded towards the destination area, but is not distributed inside it. Hence, these messages are only received by nodes within direct communication range of the source node or the last forwarding node outside the destination area, as depicted in Figure 2.9.

In addition to these schemes, a geographical adaption of the unicast, the *geographical unicast*, is defined. It is intended for unidirectional communication from one source station to a single destination station, is defined. Thereby, a message may be transmitted directly, if source and destination are adjacent stations, or forwarded by multiple intermediate stations, otherwise. Therefore, a C2X message contains a destination node's identifier and its last known geographical position. Due to the high mobility, the destination position is regarded as approximated target during determining the forwarding route, only. Additionally, a hop-limit and time information regarding the message validity as well as target's position time stamp may be provided to restrict message delivering efforts. Such a communication scenario is depicted in Figure 2.10. Within C2X communication the geographical unicast scheme may be applied, e. g., on PVDMs, since these messages are intend to be received by a single Roadside ITS Station.

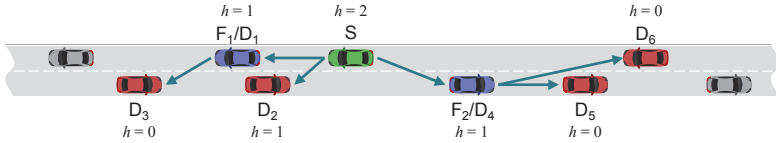
In contrast to other presented message distribution schemes, the *topologically-scoped broadcast* does not rely on geographical information. Instead, the message contains a hop-limit h , thus, each receiving node is decreasing the hop-limit by one and forwards the message as long as

$$h > 0 \quad (2.3)$$



cf. [C2C07]

FIGURE 2.10.: A C2X communication scenario based on the *geographical uni-cast* scheme. The source node S is transmitting a message to the destination node D via multiple intermediate forwarding nodes F_i .



cf. [C2C07]

FIGURE 2.11.: A C2X communication scenario based on the *topologically-scoped broadcast*, with a hop limit of $h = 2$. The message originated by the source S is retransmitted by receiving nodes F_i as long as the hop limit is not reached.

holds. The topologically-scoped broadcast is used for communication from one source to all station within the ad-hoc network and the respective topological scope. Hence, each receiving node is a destination and each, but the leave nodes, is a forwarder. An according communication scenario is depicted in Figure 2.11. Within C2X communication, the topologically-scoped broadcast scheme with a hop-limit of

$$h = 1 \quad , \quad (2.4)$$

is, e. g., applied to CAMs.

Decentralized Congestion Control

Car-to-X communication is based on a wireless network without any central controlling. Thus, messages might collide frequently such that they cannot be decoded by the receiving station.

Hence, a *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) scheme is applied. Thereby, each transceiver listens if there is any communication on the channel and starts a transmission only in the case that the channel is free. Otherwise, if the channel is busy, the transceiver waits for a time period randomly selected out of a specific range before the channel state is checked again.

Nevertheless, collisions will occur, since the channel might be free at listening time but busy when the transmission is started or it might be free at the station's position,

but an adjacent station has already started a transmission and the signal does not have reached the sending transceiver, yet. Due to restrictions of wireless communication, it is almost impossible to detect such message collisions.

Since message collisions become more frequently with increasing channel load, *Decentralized Congestion Control* (DCC) is applied to avoid collisions as far as possible. Selected aspects regarding DCC are outlined and discussed in the following.

First of all it has to be regarded that C2X communication aims towards an improvement on road safety. Hence, to ensure a certain *Quality of Service* (QoS), highly safety related messages shall be prioritized. Accordingly, messages include a *traffic class* [ETSI11a] attribute, determining their priority. The actual traffic class depends on the message type, the use-cases, as well as the current scenarios.

To apply both, a prioritization and a reduction of sent messages, within C2X communication CSMA/CA is adjusted accordingly. Hence, the actual range, the waiting time is selected out of if the transceiver detects a busy channel, is determined by the current message's traffic class, the current overall channel load, and the number of tries the transceiver has already started to transmit the current message [ETSI11a].

A complementary approach is based on reducing the transmission power [ETSI11a]. This way, the number of reached and, thus, affected station is reduced. In [TMSH06] such an approach is evaluated, especially regarding *fairness*. However, besides the benefits of this approach, it has to be considered that reducing the transmission power decreases the transmission range and, hence, increases the number of required hops to forward a message. This again increases the total number of messages to be sent.

A more flexible approach on radiation control, the *Secure C2X Beamforming*, is introduced in [SSH09] and particularly detailed in Section A.2. Thereby, targeting on improving security aspects, the method of radiation control by means of beamforming is applied to C2X communication. Thus, an antenna's radiation is not distributed equally into all directions, but focused towards a receiver's position. Regarding DCC aspects, this approach facilitates a reduction of medium usage within unintended directions and, hence, reduces the overall channel usage. However, since, as outlined in Section A.2, Secure C2X Beamforming relies on especial designed antennas, this approach is not applied within current C2X communication designs and standards.

On the other hand, DCC might not only be applied on physical and medium access layer but additionally on higher levels. Hence, e. g., the frequency at which CAMs

are generated is reduced [ETSI11b] by adapting the message generation criteria as outlined in Section 2.3.1, if the overall channel load increases. However, this results in less updates such that C2X applications have to rely on outdated data.

Additionally, the message repetition rate, for *forwarding*, and *keep-alive forwarding*, as applied by a message's originator might be reduced. However, it has to be regarded that this adaption results in slower message distribution such that receiving ITS stations may not receive messages in time.

To provide DCC, within C2X communication multiple approaches are combined. Hence, channel load and traffic class adaptive CSMA/CA, transmission power adaption, and message frequency reduction are applied [ETSI11a]. However, as the evaluation in [ACM⁺13] shows, the actual quality of this combination of different techniques depends highly on the selected parameters, but demonstrates a promising approach.

2.4. Pseudonym Changes

Within Car-to-X communication messages containing vehicle's position, speed, heading, and further meta-data are sent periodically with a frequency of 1 Hz up to 10 Hz as detailed in Section 2.3.1. These messages can easily be linked together to reconstruct the entire path the vehicle has moved [GH05] as outlined in Section A.1.2.

Since, firstly, the number of registered vehicles highly correlates with the number of driving licenses within each household [ADAC11] and, additionally, the total number of driving licenses [BAST07] and total registered vehicles [BK08] correlate, each vehicle may be mapped to almost on person. Consequently, from tracing the movements of a specific vehicle it can be concluded to the movements of a specific person and its identity with high reliability. This opens the goal for countless undesired privacy infringements by unauthorized adversaries and, hence, an immense loss of anonymity. To assure complete *anonymity* a person's identity must not be revealed by any transmitted data [ECK13].

On the other hand, in the case of, e. g., hit-and-run or other criminal acts, determining involved vehicles is desired. Accordingly, a certain level of accountability by means of resolving determined messages to a specific vehicle and, hence, a person's identity by law enforcement agencies is intended.

To provide a compromise between the contrary requirements of anonymity and accountability, a concept based on *pseudonymity*, a weaker form of anonymity, is established within C2X communication [IEEE06]. Thereby, *pseudonyms* are

consulted, which are not linkable directly to a vehicle, but may be resolved by respective authorities, if required [ECK13]. However, equipping Vehicle ITS Stations with a single pseudonym does not solve the issues of privacy infringement. Instead, the risk of easy tracing and resolving the driver's identity is still given, as stated above.

An approach based on *pseudonym changes* is commonly accepted as a promising concept to improve privacy and facilitate pseudonymity in C2X communication. Thereby, every VIS possesses multiple pseudonyms and changes them frequently. During a pseudonym change any information, which is included in a message and may serve as an identifier, has to be replaced.

Accordingly, each *pseudonym* has to provide new identifiers for all layers of the C2X communication stack. This includes network address, station ID, IP address, public and private keys with according certificates, etc.

Moreover, even application specific data may be exploited to identify a vehicle and, hence, to map two individual pseudonyms. Especially information with high resolution or combinations of different data, like

- vehicle dimensions with a resolution up to millimeters as used in CAMs [ETSI11b],
- positions and dimensions of single detected situations transmitted in DENM or even sets of situations as proposed in [C2C14],
- multiple positions and probe values as included in PVDM as detailed in Section 2.3.3, or
- traces as used in CAMs [ETSI11b] or within situations in DENMs as proposed in Section 3.2.2,

are extremely individual and, hence, may be easily exploited as unique identifiers. Accordingly, generation of suchlike "identifiers" has to be prevented. Thus, the author of this thesis proposes that

- CAMs may provide vehicle dimensions in decimeters instead of millimeters and the included trace should be reset with every pseudonym change,
- previous detected situations should not be included in DENM after a pseudonym change, as applied in Section 3.2,
- PVDMs have to be encrypted,
- within event detection, as proposed in Section 3.2.2, new messages have to be triggered before the pseudonym change is applied, such that traces included in DENMs do not contain positions gathered before and after the pseudonym change.

Due to the necessity of changing or avoiding identifiers within various instances of a C2X system, the concepts of *Pseudonym Change* has to be deeply integrated within every single layer of the C2X communication stack.

The concept of pseudonymity with pseudonym changes is applied to Car-to-X communication by issuing sets of multiple pseudonyms to ITS stations by central authorities. In order to achieve these *short term identities*, vehicle stations send an according request to the responsible authority. This communication has to be secured by means of encryption and digital signatures. Thereby, a vehicle's *long term identity* is used to authenticate the station towards the pseudonym issuer. Thus, the respective authority may resolve each pseudonym to a corresponding static and unique identity.

A long term identity is preferably assigned on vehicle manufacturing or on vehicle registration. However, due to possible corruption of long term identities, which cannot strictly avoided as outlined in Section A.1.1, interfaces to exchange and revoke identities have to be foreseen. In contrast suchlike interface are not required for short term identities, due to their short validity duration.

However, even if applying the concept of changing pseudonyms is commonly used within field operational tests, e. g., in sim^{TD} [SIMTD10a], preliminary standards [IEEE06] and accepted as one of the promising approaches to ensure a certain level of privacy, tracing cannot completely impede by this technique [SKL⁺06]. Advocating, e. g., a Kalman filter-based approach to trace vehicles, pseudonym changes may be revealed easily [WMKP10].

Consequently, additional complementary techniques, e. g., *Mix-Zones* [BS04], may be applied to C2X communication systems by means of establishing static Mix-Zones [LBV07] on suitable locations like, e. g., intersections [FRF⁺07]. Hence, effectiveness of pseudonym changes is increased and improvements to driver's privacy are reached [DDS10]. Moreover, additional enhancements are achieved by forming *Dynamic Mix-Zones* upon vehicle's request [YMM13]. Thereby, a secret group key may be established, e. g., based on geographical cells [SPH11]. Additionally, advanced key agreement schemes, e. g., based on the Diffie-Hellman key exchange [DH76], may be adopted to the C2X communication domain [SÇH11] facilitating dynamic group management, i. e., joining and leaving the group.

2.5. Area and Coordinate Definitions

In order to exchange information about geographical areas and positions between different ITS stations, their shapes and representation has to be agreed on. Hence,

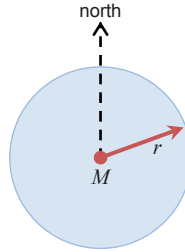


FIGURE 2.12.: The two parameters, i. e., M and r , of a circle as given in a DENM.

within the following sections, regarded geographical areas and their representation, is outlined in the first place.

While coordinates are encoded within the WGS 84 coordinate system between ITS stations and components within a station, for internal representation and calculation the use of a different representation might be selected. Hence, multiple possible coordinate systems and transformations are detailed and discussed subsequently.

2.5.1. Area Definition, Representation, and Encoding

In order to refer a geographical area, the shape of that area is given by either a *circle*, an *ellipse*, or a *rectangle* [ETSI10c].

A circular area is defined by a center point M and a radius r as depicted in Figure 2.12.

To define not only axis-oriented, but also arbitrary oriented rectangles, there are different possible sets of parameters evaluated in field operational tests. In the German research project sim^{TD} , e. g., two points and a width are exploited [SIMTD09j]. Thereby, the points specify two neighbored edges and, therefore, the length and a border of the area. The width is added to the left hand side of that border. However, in current standardization a rectangle is defined by the four parameters as detailed in Table 2.3.

Thereby, M is given as a WGS 84 coordinate, a and b are given in meters, and θ is an angle in degrees, clockwise from north. Such a rectangle, including its parameters, is depicted in Figure 2.13.

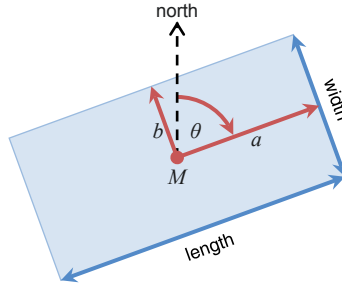
Finally, an ellipse is expressed with the same four parameters as used for a rectangle, except that an ellipsoid shape is calculated as depicted in Figure 2.14.

Defining these three shapes in this way provides major advantages. Firstly, the representations may be encoded within a DENM in a very similar manner. Since the four parameters, i. e., M , a , b , and θ , for a rectangle and an ellipse are identical, they,

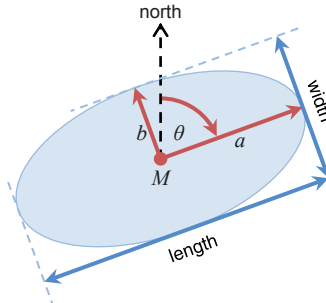
M	the center of the rectangle (longitude, latitude)
a	the half of the length (distance from the center to the shorter side)
b	the half of the width (distance from the center to the longer side)
θ	the clockwise rotation against north (azimuth angle)

cf. [JH13]

TABLE 2.3.: Summary of the four parameters defining a rectangle within a DENM.



cf. [JH13]

FIGURE 2.13.: The four parameters, i. e., M , a , b , and θ , of a rectangle as given in a DENM.FIGURE 2.14.: The four parameters, i. e., M , a , b , and θ , of an ellipse as given in a DENM.

obviously, may be encoded in exactly the same way. However, even the parameters of the third shape, i. e., M and r , may fit into this representation. Thereby, the center point M is already given, a and b are set equally to the radius r , and θ is set to 0. Secondly, the size of the shape may be changed straightforwardly. Since all shapes are expressed based on the center point in combination with the expansion from that point, they may be magnified or shrunk by just increasing or decreasing a , b , or r , respectively. Furthermore, rotation is applied by only adapting θ . Finally, a Cartesian coordinate system based on the shape may be easily constructed as further detailed in Section 4.3.2.

Within the context of the Weather Hazard Warning application as presented in this thesis, rectangles are exploited to define geographical areas.

2.5.2. Coordinate Definition and Representation

Geographical positions, e. g., provided from a GPS receiver, are commonly given in coordinates according to the *World Geodetic System 1984* (WGS 84) coordinate system. In WGS 84 coordinate system each position is refereed by its two spherical coordinates *longitude* λ and *latitude* φ .¹⁴ As mentioned before, in C2X communication points provided in DENMs are given in such coordinates.

However, for most mathematical operations, it is advantageous not to deal with spherical coordinates but with coordinates in a two dimensional Cartesian coordinate system. Additionally, units within the coordinate system should be interpreted as meters. This simplifies transferring sizes, like distances, lengths, and areas, into the real world. Finally, such a coordinate system can be interpreted as a two dimensional vector space $\mathbb{R}^2$ by using the point's coordinates as components of the point's position vector. Consequently, in the context of this thesis, the conversion of WGS 84 coordinates into a two dimensional Cartesian coordinate system is selected to achieve efficient calculations within a C2X application.

Subsequently, three selected coordinate transformations are detailed and compared.

Universal Transverse Mercator Coordinate System

The *Universal Transverse Mercator* (UTM) coordinate system [DMA89] is a possible choice for such a coordinate system. Positions in UTM coordinates are given by three parameters, the *UTM zone*, an *easting*, and a *northing*.

Thereby, based on the WGS 84 ellipsoid, the world is divided around the equator

¹⁴ In fact, there is additionally an *elevation*, i. e., the height above the reference ellipsoid, provided. However, in the context of this thesis, the elevation can be omitted.

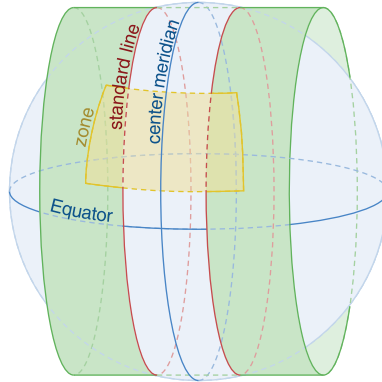


FIGURE 2.15.: An adapted transverse Mercator projection as utilized within the transformation of WGS 84 coordinates into the UTM coordinate system. Thereby, the earth's surface is cut by the zone's projection cylinder.

into 60 *zones*, each a 6° wide band of longitude.¹⁵ The zone numbering increases eastward, starting at the *International Date Line* with zone 1, which covers 180° to 174° west up to zone 60, which covers 174° to 180° east.

For each zone, a slightly adapted *transverse Mercator projection* is applied. Thereby, the earth's surface is projected onto a cylinder. To minimize the overall distortion, the cylinder is cutting the sphere's surface east and west of the center meridian of the zone.¹⁶ At the equator, these *standard lines* are located $\approx 1.5^\circ$ to the east and west, respectively, of the zone's center meridian. This way, the scale factor between the standard lines is less than 1 with a minimum of 0.9996 at the center meridian of a zone, at the standard lines the scale factor is 1, and outside it is above 1. Such an adapted transverse Mercator projection is illustrated in Figure 2.15.

Based on these zones, easting is defined as the distance in meters to the center Meridian of the respective zone.¹⁷ In contrast, northing is simply defined as the distance in meters to the equator.¹⁸ Consequently, easting is unambiguous only within its own zone, while northing is globally unique.

The conversion of a WGS 84 coordinate into the UTM system can not be explained within a few formulas only. However, the algorithm and related respective equations

¹⁵ With the exception of a few non-standard zones.

¹⁶ At a pure transverse Mercator projection the projection cylinder would touch the sphere at the zone's center meridian.

¹⁷ To avoid negative distances in the left hand side of each zone, an offset of 500 km is added.

¹⁸ Again, to avoid negative distance, 10 000 km are added within the southern hemisphere.

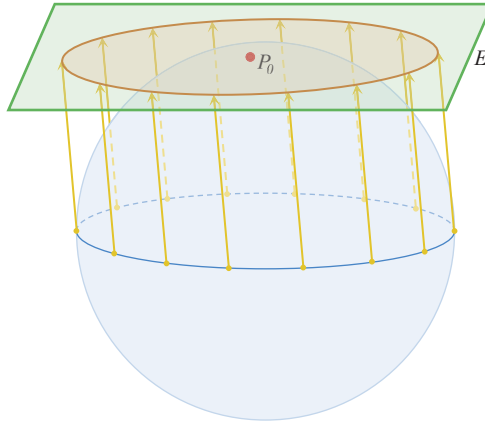


FIGURE 2.16.: The orthographic projection maps points of a sphere onto a flat projection plane E , which touches the sphere at the reference point P_0 . Thereby, positions located on the opposite side of the sphere as the reference point are clipped and not mapped to the plane.

are extensively detailed in [DMA89].

To exploit UTM coordinates as a two dimensional Cartesian coordinate system, easting¹⁹ and northing have to be interpreted as x- and y-coordinates, respectively. This approach is implemented and tested within the *Road Weather Warning* application in context of the German research project *sim^{TD}* [SIMTD]. However, the handling of UTM coordinates near the borders of UTM zones and, moreover, of points positioned in different zones, is rather challenging.

Orthographic Projection

A second approach to achieve a two dimensional Cartesian coordinate system is to apply an *orthographic projection*. Thereby, the earth's surface is projected onto a tangent projection plane E , where an intuitive Cartesian coordinate system is given. The projection plane touches the surface of the earth, which is assumed to be a perfect sphere, at a reference position P_0 . Such an orthographic projection is depicted in Figure 2.16.

Due to the projection of a spherical surface onto a flat plane, the distortion, in terms of shrunk distances, grows with an increasing distance to the reference point. Finally, at a distance of 90° the distortion reaches its maximum and no projection of points placed beyond this limit is possible anymore. However, if the reference

¹⁹ For easting, the current UTM zone has to be regarded, in addition.

position P_0 is set, e. g., to the current vehicle's position, the orthographic projection provides a high accuracy within the area close to the vehicle. Only positions located far away from the vehicle, where no high accuracy is needed, are significantly affected by the projection's distortion.

The orthographic projection is applied to an arbitrary WGS 84 coordinate P with longitude λ and latitude φ by referencing a reference point $P_0 = (\lambda_0, \varphi_0)$ according to, e. g., [SNY87], by

$$x = r \cdot \left(\sin(\lambda - \lambda_0) \cdot \cos \varphi \right) \quad (2.5)$$

$$y = r \cdot \left(\sin \varphi \cdot \cos \varphi_0 - \cos \varphi \cdot \sin \varphi_0 \cdot \cos(\lambda - \lambda_0) \right) , \quad (2.6)$$

whereas r is the earth's radius with

$$r = 6371000.8 \text{ m} \quad (2.7)$$

and x and y are the Cartesian coordinates of P . Thereby, the point P is located outside the projection plane and no projection is possible if

$$0 > \arccos \left(\sin \varphi \cdot \sin \varphi_0 + \cos \varphi \cdot \cos \varphi_0 \cdot \cos(\lambda - \lambda_0) \right) \quad (2.8)$$

holds.

The projection of a Cartesian coordinate back to its WGS 84 representation is achieved by applying

$$\lambda = \lambda_0 + \arctan \left(\frac{x \cdot \sin \zeta}{\rho \cdot \cos \varphi_0 \cdot \cos \zeta - y \cdot \sin \varphi_0 \cdot \sin \zeta} \right) \quad (2.9)$$

$$\varphi = \arcsin \left(\sin \varphi_0 \cdot \cos \zeta + \frac{y \cdot \cos \varphi_0 \cdot \sin \zeta}{\rho} \right) \quad (2.10)$$

with

$$\rho = \sqrt{x^2 + y^2} \quad (2.11)$$

$$\zeta = \arcsin \frac{\rho}{r} . \quad (2.12)$$

Delta-Lambda-Equator Coordinates

A third possible coordinate transformation again builds up the coordinate system based on a reference position P_0 . Thus, no reference to a respective zone is needed. Thereby, Cartesian coordinates are achieved by taking the distance in meters from the reference point's longitude λ_0 (the *reference meridian*) Δ_λ as x-coordinate and

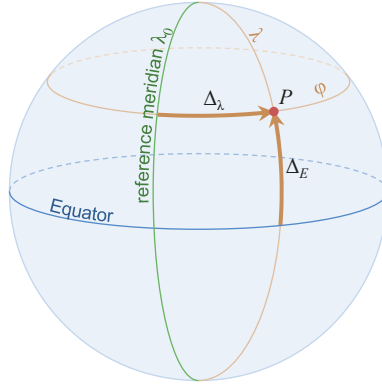


FIGURE 2.17.: Within the DLE coordinate system the x- and y-coordinates of a point P are given by the points distance to a reference meridian Δ_λ and distance to the equator Δ_E , respectively.

the distance in meters to the Equator Δ_E as y-coordinate, respectively. For a point P this approach is depicted in Figure 2.17.

The basic idea of this approach was firstly proposed by the author of this thesis in [JH13]. Thereby, the reference meridian was set to the *International Reference Meridian*, such that $\lambda_0 = 0^\circ$ holds. In contrast to this static reference meridian, for the novel *Delta-Lambda-Equator* coordinates (DLE) the reference meridian might be selected dynamically based on the current scenario.

For simplification, within the coordinate transformation, the earth again is assumed to be a perfect sphere. The radius r of this sphere is set to the mean radius of the WGS 84 ellipsoid, i. e.,

$$r = 6371\,000.8 \text{ m} . \quad (2.13)$$

An arbitrary WGS 84 coordinate with longitude λ and latitude φ is converted into a point $P = (x, y)$ regarding a reference meridian λ_0 by utilizing the arc angle²⁰ such that

$$x = r \cdot (\lambda - \lambda_0) \cdot \cos \varphi \quad (2.14)$$

$$y = r \cdot \varphi . \quad (2.15)$$

Such a point P of the Cartesian coordinate system is converted back into a WGS 84

²⁰ In contrast, in [JH13] the respective x- and y-coordinates are determined based on the calculation of the orthodromic distance. Thereby, the equation was simplified by $\sin(0) = 0$ and $\cos(0) = 1$. However, by using the arc angle, the calculation is further simplified significantly.

coordinate by applying

$$\lambda = \frac{x}{r \cdot \cos \varphi} + \lambda_0 \quad (2.16)$$

$$\varphi = \frac{y}{r} \quad (2.17)$$

This advanced approach is also detailed in [JH15].

As within orthographic projection, thereby the distortion growths in relation with the distance to the reference position too. In contrast, distortion growths in relation with the distance to the reference meridian, i.e., the x-direction only. Along the y-direction inaccuracy is given mainly by the assumption that the earth is a perfect sphere. Moreover, although inaccuracies may get significant large, even for x-direction, there is no restricting maximal distance to be regarded.

However, within several kilometers around the reference point no noticeable distortion has to be considered. Since for Car-to-X applications the near area around the vehicle is regarded, the reference point may be set to, e.g., the vehicles current position, to achieve highest transformation accuracy for relevant areas.

In order to prove the usability of DLE coordinates, this concept was implemented and extensively evaluated within the *Weather Warning* application in context of the research project DRIVE C2X [DRIVE] as further detailed in Section 6.4 and Section 7.1.

Argumentative Comparison and Recommendation

Comparing the presented approaches, it is obvious that all three coordinate systems, of course, cannot be used in a global manner, i.e., handling coordinates that are far apart from each other. Nevertheless, in local scale of multiple kilometers, as needed for C2X applications, all three are highly appropriate.

However, conversion of WGS 84 into UTM coordinates and vice versa needs extensive computations²¹, while for applying an orthographic projection or conversion into the DLE coordinates just the respective enumerated simple equations have to be applied. Since computation resources are highly restricted in automotive domain, the high transformation efficiency is a huge advantage of the proposed transformation into DLE coordinates. In addition, relative positioning and distances in local scale do not suffer from inaccuracies based on simplifying the earth as a sphere. Hence, a high accuracy for Car-to-X communication purposes is ensured.

Consequently, the author of this thesis recommends to use the outlined DLE coordinates to convert WGS 84 coordinates into a two dimensional Cartesian coordinate

²¹ The related formulas exceed the scope of this thesis, but are detailed in [DMA89].

system. For the context of this thesis, it is accordingly assumed that points are given in or converted into the proposed DLE coordinates.

Regarding Coordinates within the Vector Space $\mathbb{R}^2$

As mentioned, for some mathematical calculations positions may be regarded as points not only within a two dimensional Cartesian coordinate system, but within a two dimensional vector space $\mathbb{R}^2$. For all three detailed coordinate systems, a transformation into the vector space is possible.

Within $\mathbb{R}^2$ for each point P , there is the *position vector* $\vec{P}$. A position vector $\vec{P}$ for the point $P = (x, y)$ is defined as

$$\vec{P} = \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} . \quad (2.18)$$

Hence, due to the current needs, each position may be regarded as point with x- and y-coordinate in context of a two-dimensional Cartesian coordinate system or as point within the vector space $\mathbb{R}^2$ represented by the according position vector. Thus, calculations as detailed in Sections 3.2.3, 4.3.1, 4.3.2, 4.3.3, and 5.1, respectively, are partially performed within a vector space.

Weather Hazard Warning Application in Car-to-X
Communication

Concepts, Implementations, and Evaluations

Jaeger, A.

2016, XXIII, 214 p. 92 illus., Softcover

ISBN: 978-3-658-15315-1