Universität Ulm
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# Efficient Information Dissemination in VANETs

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# Zusammenfassung

Durch die spontane, drahtlose Kommunikation von Informationen zwischen Fahrzeugen können viele neuartige Anwendungen realisiert werden. Dazu zählen primär Anwendungen mit dem Ziel, die Verkehrssicherheit durch die Vermeidung von Gefahrensituationen zu erhöhen. Auf diese Weise können beispielsweise Fahrzeuge an einem Stauende herannahende Verkehrsteilnehmer warnen, so dass auch ohne Sichtkontakt die Situation rechtzeitig erfasst und dadurch ein Auffahrunfall vermieden werden kann. Es gibt außerdem eine Reihe weiterer Anwendungsarten, zum Beispiel Anwendungen, um das Fahren effizienter zu machen, oder auch sogenannte Business- und Entertainment-Anwendungen.

Diese vielfältigen Anwendungsarten stellen unterschiedliche Anforderungen an das Kommunikationssystem: insbesondere Anwendungen, die andere Verkehrsteilnehmer über eine Gefahrensituation warnen sollen, erfordern die Adressierung von mehreren Fahrzeugen, die sich beispielsweise in einer bestimmten geographischen Region befinden. Viele Anwendungen erfordern die Dissemination von Informationen über mehrere Fahrzeuge (Hops) hinweg, um möglichst auch weit entfernte Fahrzeuge erreichen zu können. Kommunikationsprotokolle, die solche Anwendungen auch mit mehreren millionen Teilnehmer unterstützen sollen, müssen neben den unterschiedlichen Anforderungen der Anwendungen auch nichtfunktionale Anforderungen berücksichtigen. Aufgrund der Vielzahl der Anwendungen ist eine Berücksichtigung der Einzelanwendungen nicht praktikabel. Daher ist der erste Beitrag dieser Arbeit die Kategorisierung der Anwendungen anhand deren Zweck und deren Anforderungen an das Kommunikationssystem. Dadurch ist es möglich, Kommunikationsprotokolle aufgrund wenigen Anforderungen zu untersuchen und zu bewerten. So ist eine Aussage über die Eignung des untersuchten Protokolls für ganze Klassen von Anwendungen möglich. Darauf aufbauend stellt diese Arbeit sogenannte Kommunikationsmuster vor, die für die Realisierung der An-

wendungen der unterschiedlichen Klassen eingesetzt werden können.

Die untersuchten Anwendungen zeigen auf, dass das Versenden von Informationen an mehrere Teilnehmer über einen sogenannten Broadcast die häufigste Kommunikationsart in Fahrzeug-Fahrzeug-Netzen ist. Wenn Nachrichten über mehrere Hops weitergeleitet werden, ist diese Art der Informationsdissemination eine herausfordernde Aufgabe, vor allem in Anbetracht der höchst dynamischen Netzwerkcharakteristika, die in Fahrzeug-Netzen vorherrschen. Diese Arbeit zeigt auf, dass klassische Ansätze für die Umsetzung von solchen Broadcasts in Fahrzeugnetzten unzulänglich sind. Darauf aufbauend ist die Einführung von neuartigen Ansätzen für die effiziente Informationsdissemination in Fahrzeug-Fahrzeug-Netzen der Hauptbeitrag der vorliegenden Arbeit. Diese sogenannte hybride Disseminationsverfahren kombinieren die positiven Eigenschaften mehrerer Protokoll-Klassen, wobei zugleich ihre Nachteile beseitigt bzw. wenigstens abgeschwächt werden. Die Vorteile dieser hybriden Protokolle gegenüber klassischer Ansätze werden mittels Simulationen aufgezeigt. Diese Ergebnisse zeigen deutlich, dass die vorgeschlagenen Ansätze den klassischen Ansätzen weit überlegen sind, insbesondere in dichten Netzen und bei hoher Mobilität der Fahrzeuge. Daher handelt es sich hierbei um vielversprechende Disseminationsprotokolle für Fahrzeugnetze, die den vielfältigen Anwendungsanforderungen genügen und unter unterschiedlichen Netzwerkbedingungen eingesetzt werden können. Folglich ist diese Arbeit ein grundlegender und wichtiger Beitrag, um über die drahtlose Kommunikation zwischen Fahrzeugen das Autofahren sicherer, effizienter und unterhaltsamer zu machen.

# Abstract

Vehicular Ad-hoc Networks (VANETs) represent a promising approach to realize novel applications by exchanging information between vehicles over a wireless medium. Primarily safety applications are counted among them, which intend to increase the road safety by avoiding dangerous situations. For example, vehicles located at the end of a traffic jam could warn approaching vehicles. A driver of such a car could register the situation in time, even without line of sight and avoid a rear-end collision accident. Furthermore, there are a number of other VANET applications, e.g. applications intended to make driving more efficient or so called business and entertainment applications.

This variety of applications impose different requirements onto the communication system: So for example, applications which inform arriving vehicles about a hazardous situation, typically need to address multiple cars located in a geographic region. Furthermore, many applications need to disseminate messages over multiple hops, to favorably reach also distant vehicles. In order to facilitate such applications possibly with several million of network participants, besides the diversity of application requirements also non-functional requirements must be considered by such communication systems. Due to the multitude of envisioned applications for VANETs, it would be unfeasible to analyze protocols one by one by considering application requirements. Therefore, the first contribution of this work is a classification of VANET applications by considering their purpose and network layer properties. This way, communication protocols can be analyzed by considering only a few key requirements, but which stand for a whole group of applications. Based on this, this work presents several so called communication patterns, which are the building blocks of the communication system to support the applications of the identified classes.

The examined applications reveal the importance of the dissemination of information to

several destinations by so called broadcast messages. If such messages are relayed via multiple hops, this kind of information dissemination is a challenging task, especially in the presence of high dynamic network characteristics as is the case in VANETs. This thesis reveals, that conventional approaches are inadequate for the realization of such broadcast protocols in VANETs. Based on these findings, the main contribution of this work is the introduction of novel broadcast protocols, designed for the efficient information dissemination in VANETs. These so called hybrid broadcast protocols combine the advantages of different protocol classes, at the same time eliminating – or at least alleviating – their weaknesses. For the comparison extensive simulations were done, which clearly show the superiority of the proposed protocols over classical approaches, especially in the presence of high network densities and high mobility of vehicles. Therefore, these are promising novel information dissemination protocols designed for VANETs, meeting the diversity of applications' requirements and varying network conditions. Consequently, this thesis is a fundamental and important contribution to make driving more safe, efficient and entertaining through wireless ad-hoc communication between vehicles.

# Acknowledgements

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# CHAPTER 1

# Introduction

Vehicular Ad-hoc Networks (VANETs) enable promising new possibilities to enhance traffic safety and efficiency, moreover, to enhance the driving experience. Therefore, a variety of VANET applications were proposed, which intend to achieve the afore mentioned goals. Such applications are build upon different communication mechanisms, which can be regarded as the building blocks of future vehicular applications. These communication protocols disseminate information over a mobile ad-hoc network composed of vehicles and Road Side Units (RSUs). It is obvious, that providing efficient and reliable communication services for VANETs is a challenging task, therefore this thesis evaluates such protocols extensively and proposes novel approaches. Their applicability for VANETs are shown by simulations.

This chapter provides a short introduction into this exciting research topic in Section 1.1[1], outlines the contribution of this work in Section 1.2, and gives an overview of the thesis' structure in Section 1.3.

## 1.1 Motivation

The vision of VANETs is that vehicles communicate spontaneously, in an ad-hoc manner over a wireless medium. Based on this Inter-Vehicle Communications (IVC), vehicles exchange important information, e.g. about road conditions and hazardous situations. Moreover, such information can be propagated via multiple hops, thus making the dissemination of

[1] Adapted from [1].

important information possible over longer distances.

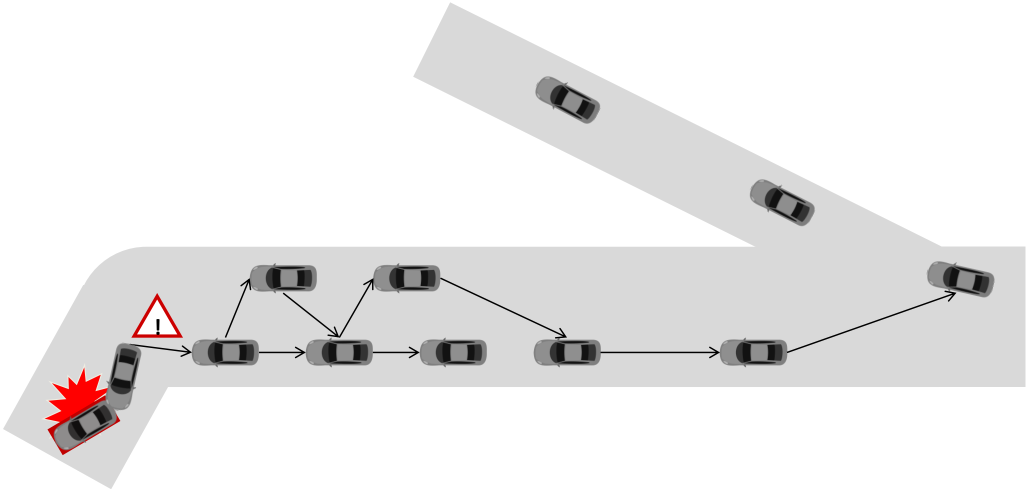

Figure 1.1: Example scenario for VANET appications.

An example is shown in Figure 1.1. An accident occured in a curve, the affected vehicles broadcast a warning message to inform arriving vehicles. The drivers of these vehicles can be warned in time to decrease their driving speed, thus avoiding a potential collision. Moreover, if a traffic jam is forming because the broken down vehicles make passing impossible, the vehicles could use VANET communication to cooperatively analyze the dynamics of the traffic jam and to inform approaching vehicles about the new dangerous situation. If such information is propagated over multiple hops, other cars can take an exit, thus reducing their travel time drastically. Also an approaching emergency vehicle could warn other traffic participants by using wireless communication.

The multi-hop communication is the key advantage of this kind of safety applications compared to conventional safety systems. Whereas conventional safety systems only rely on information sensed in the direct neighborhood by onboard sensors of a vehicle, active safety applications based on IVC can utilize information generated by nodes multiple hops away. Moreover, such information can be enriched on the way with information sensed by relaying cars. This greatly enhances the potential of VANET applications. Thus, advantage of multi-hop communication is twofold:

- Having information about distant hazardous situations like an accident ahead or icy road, the driver can be warned in time, thus being able to completely avoid the dangerous situation.

- Aggregating information from multiple cars enables retaining information on a higher semantic level. This way, applications like cooperative traffic jam warning and cooperative parking place detection can be realized.

The enabling technology for such applications is the wireless ad-hoc communication between vehicles. Especially the dissemination of messages in a specific geographic region represents a fundamental service in VANETs to which we refer to as Geographic Broadcast (GeoCast). This communication paradigm is used by many applications to enhance traffic safety and efficiency but it can also serve as a basic mechanism for other routing protocols. Because of its relevance in the domain of vehicular networks, it is of key importance that the communication protocol enables efficient message dissemination.

The realization of a robust and efficient broadcast mechanism is a challenging task due to the wide range of applications envisioned, the rigorous requirements of safety applications, and the special network characteristics of vehicular networks. Examples for such characteristics are the highly dynamic network structures, where due to the high node velocities the topology changes rapidly over time. Furthermore, in vehicular networks two extreme situations occur regularly: we may face on the one hand partitioned networks on rural roads especially at night hours, and on the other hand, an extreme high node density in traffic jams at rush hours. Moreover, the wireless communication medium represents a scarce resource considering the limited bandwidth and the amount of potential cars and applications competing, and thus, they potentially disturb each other resulting in packet collisions and message losses.

Because of the importance of geographic broadcast mechanisms for intelligent transportation systems, in this thesis we investigate novel broadcast protocols which enable an efficient and dependable dissemination of information over multiple hops, even in the presence of extreme network characteristics like traffic jams or partitioned networks.

## 1.2 Aims of this Work

There are many proposals for multi-hop dissemination protocols on the research fields of ad-hoc and sensor networks. Unfortunately, those approaches cannot be adopted directly for the domain of vehicular applications. The main reasons are the manifold vehicular application requirements and the high dynamicity of VANETs. Although there are a few proposals for such dissemination protocols for VANETs, there is no evaluation of VANET protocols which comprehensively consider the application requirements and network characteristics. Most of the present research on vehicular applications take the efficient and reliable dissemination protocols for granted.

Therefore, the goal of this work is to investigate and to propose efficient multi-hop information dissemination protocols for VANETs. This includes both, the comparison of existing approaches and the elaboration of novel broadcast mechanisms which fit the requirements of VANET applications and those imposed by the high dynamicity of vehicular networks. To achieve this goal, this thesis provides the following contributions.

1. **Review and classification of VANET applications**
   In order to understand the requirements imposed by the different vehicular applications, these applications need to be reviewed and classified from a network perspective. This classification helps to understand these key requirements of the dissemination protocols.

2. **Review and classification of IVCs**
   VANET communication is based on wireless communication between vehicles and RSUs. First of all, the characteristics of the used radio hardware has to be summarized. These provide the determining factors of vehicular communications. Based on this information, basic communication patterns can be derived, which can be used to fulfill the different application level requirements. Moreover, the characteristics of vehicular networks must be reviewed, which reveal the non-functional requirements of the dissemination protocols.

3. **Review and classification of broadcast protocols**
   As a groundwork for the investigation of novel broadcast approaches, a comprehensive review of existing approaches together with a classification is provided. This evaluation includes approaches from neighbor research areas, like ad-hoc, mobile ad-hoc, and sensor networks. The advantages and disadvantages of the approaches are discussed based on that classification. These results are incorporated into the design of novel approaches as described in the following step.

4. **Introduction and evaluation of novel multi-hop broadcast protocols for VANETs**
   The main focus of this thesis is the efficient multi-hop dissemination of information in VANETs. Therefore, novel hybrid broadcast approaches are proposed, which try to combine the advantage of different approaches, alleviating their disadvantages. These protocols are evaluated by simulations with the help of metrics derived from the requirements. The results show their applicability in different VANET scenarios and clearly underline their outstanding properties, compared with other protocols.

In a nutshell we can state, this thesis establishes novel broadcast protocols, for the efficient and robust information dissemination in VANETs. These proposed protocols are designed to work in high dynamic environments as is the case of vehicular networks. They support a wide range of scenarios, be it highway or urban roads with intersections, low or high velocities of cars, sparse and even partitioned networks as e.g. on rural roads up to very dense networks as in a traffic jam at rush hours. Thus, these novel protocols represent a very promising approach for the support of a plenty of vehicular applications, which will significantly increase the road safety and driving comfort in the near future.

## 1.3 Organization

This thesis is organized as follows: In Chapter 2 the envisioned applications for VANETs are reviewed and classified based on communication requirements and user benefit. Chapter 3 reviews the basic IVC communication mechanisms, elaborates the special network characteristics of VANETs and provides a mapping of application requirements onto routing attributes. Chapter 4 reviews, classifies, and discusses different broadcast protocols. Based on these results, novel hybrid approaches are proposed in in Chapter 5. Those approaches are then evaluated by simulations in Chapter 6. Finally, the thesis is concluded in Chapter 7.

# CHAPTER 2

## VANET Applications

There are many applications envisioned for Vehicular Ad-hoc Networks (VANETs), in [2] e.g. more than 75 applications were identified. In [3] Bai et al. present a classification of applications from a network perspective. Schoch et al. categorize in [4] applications based on their purpose and the situation they are designed for. Further classifications and overview of VANET applications can be found in [5, 6, 7, 8, 9, 1, 10]. Also many publications present examples of applications.

Thus, the number of potential VANET applications is enormous and implementing them would result in a huge benefit: The number of severe accidents could be decreased significantly by safety applications, driving made more efficient by applications which help and guide the driver by providing valuable information, and also driving could be more entertaining by infotainment applications. This benefit view is one possible criteria to roughly categorize VANET applications [3], and is widely used in publications (actually most of the classification works presented above use some sort of benefit criteria classification).

Although this benefit oriented classification criteria is intuitive and it also provides a motivation view on applications, no prediction can be derived regarding the requirements of the communication systems. Therefore, this chapter introduces a classification based on both network and benefit oriented properties. This is the first important contribution of this thesis and it allows to examine VANET applications from a network perspective similar to [3]. This way a systematic evaluation of communications mechanisms can be done, by considering only a few requirements derived from the application classes. Before going into details on vehicular applications and their classification, the next section summarizes the methodology used for this purpose.

## 2.1 Methodology

The goal of this chapter is to provide a systematic classification of VANET applications based on their purpose (also called user benefit) combined with communication requirements specified by the application use-cases. Such a classification groups applications together by their purpose – and even more important – by similar network characteristics. The result is a taxonomy which can be used to systematically evaluate which communication protocols can be used for which application classes. Thus, a clear mapping from dissemination protocols to applications can be retrieved, and from that a classification of VANET dissemination mechanisms can be deduced. Another advantage of such a taxonomy is that single applications are abstracted as groups, thus, they can be examined, analyzed, and evaluated based on their group characteristics.

To achieve these goals, we proceed according to the following methodology:

1. **Literature review of VANET application classification proposals**
   In the first place, we survey in Section 2.2 the literature for existing approaches of application classifications. We use the results of this literature review to define the application requirements, and to establish an own taxonomy.

2. **Definition of relevant communication requirements**
   In Section 2.3 we define the application requirements of the communication systems. Based on these requirements the different applications are characterized serving as an input for the classification in the last step.

3. **Purpose- and communication-characteristic-based classification**
   In Section 2.4[1] the applications are finally classified based on their purpose and their requirements for the communication system. This classification is used to group the different applications envisioned for VANETs and to provide a short description of those applications.

The results of this approach is used in the next chapter, where Vehicular Communications (VC) is discussed in detail. Thus, it will be clear which communication requirements are imposed by the application groups. And even more, based on these results, evaluation metrics can be derived to compare different protocol alternatives.

[1]Parts of this section were initially published in [1].

## 2.2 Related Work

There are several VANET application classification works in the literature, most of them group applications by their functionalities, i.e. from a customer benefit perspective. Typically the main application groups are *safety oriented*, *convenience oriented*, and *commercial oriented* [3]. Most works on this area use these main classes – or some similar set – and group akin purposed applications to subgroups [2, 4, 11, 9, 12]. All these publications provide valuable application related information, which is used in this work.

| **Safety Applications** | **Non-Safety Applications** |
|---|---|
| Intersection Collision Avoidance | Traffic Management |
| Public Safety | Tolling |
| Sign Extension | Information from Other Vehicles |
| Vehicle Diagnostics and Maintenance | Other Potential Applications |
| Information from Other Vehicles | |

Table 2.1: Application characterization according to the VSC project [2].

The technical report from the VSC project [2] contains a very large collection of VANET applications together with their descriptions and the summarized application requirements of the communication system. In that work basically two main application scenarios are distinguished: *safety* and *non-safety* applications. The first category contains applications which primarily intend to avoid accidents, thus to make driving safer. The second category contains applications which intend to make driving more efficient and convenient. Safety applications are further divided into subcategories, as shown in List 2.1. This characterization is solely benefit oriented, i.e. communication requirements are not integrated into the characterization process. Although in this work infrastructure-based communication is dominating, it is to date the most complete compendium of VANET applications.

Schoch et al. provide in [4] a more differentiated purpose oriented application classification. The main categories proposed in that work are *Active safety*, *Public service*, *Improved driving*, and *Business/entertainment*, see Table 2.2 for details. These categories – together with their subcategories – are also based only on the function/purpose of the applications. Furthermore, several communication patterns are discussed which are the building blocks for those applications. In summary, that work provides a comprehensive overview of VANET communication mechanisms and also the mapping from applications to these patterns are provided.

Singh and Lego briefly categorize the applications in [12] also into the two base cate-

| **Main Category** | **Situation/Purpose** |
|---|---|
| *I. Active Safety* | 1. Dangerous Road Features |
| | 2. Abnormal Traffic and Road Conditions |
| | 3. Danger of Collision |
| | 4. Crash Imminent |
| | 5. Incident Occurred |
| *II. Public Service* | 1. Emergency Response |
| | 2. Support for Authorities |
| *III. Improved Driving* | 1. Enhanced Driving |
| | 2. Traffic Efficiency |
| *IV. Business/Entertainment* | 1. Vehicle Maintenance |
| | 2. Mobile Services |
| | 3. Enterprise Solutions |
| | 4. E-Payment |

Table 2.2: Application characterization by Schoch et al. [4].

gories from [2]. Furthermore, for safety applications the two subgroups *safety-critical* and *safety-related* are identified and described. According to the authors, both groups can be realized by using Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I)/Infrastructure-to-Vehicle (I2V) communications. Non-safety applications are mostly based upon V2I or I2V communications and are classified into the following subgroups: *Traffic Optimization*, *Infotainment*, *Payment Services*, and *Roadside Service Finder*. Beside the communication participants, these categorizations do not take into account communication requirements.

In [11] Dar et al. conduct a classification of applications by identifying vehicle groups with similar network characteristics. Furthermore, a detailed classification of wireless communication technologies is provided, including not only vehicular communication technologies, but also traditional wireless communication technologies which can be used to realize the afore described application groups. Finally, the authors give a recommendation of the usable carrier for each application group. One of the main contributions of that work is the communication requirements based application characterization. Unfortunately, this work also assumes solely infrastructure-based communication system for applications (according to [2]). Thus, those applications have only a short communication range.

In [9] also several application groups are identified and application examples with short descriptions for each group are supplied. Those application groups are then arranged into four priority classes, which share similar latency, transmission trigger and range requirements.

However, all considered applications do not exceed a communication range of 300 meters, which means they can be realized through single-hop information dissemination. Finally, the authors come to the conclusion, that VANET applications mainly can be distinguished in two categories: safety and non-safety applications. Safety applications use broadcast technology whereas non-safety applications are on-demand (event-based) and use two-way communications.

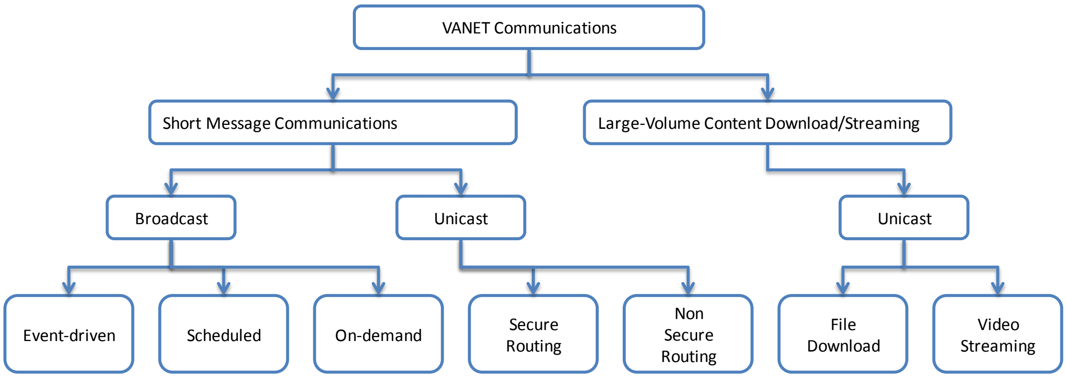


Figure 2.1: Application classification from perspective of network design [3].

Another systematic approach for application classification was chosen by Bai et al in [3]. The authors picked 16 applications and rated them according their communication requirements like application participants, transmission range, and trigger condition. These application requirements were then translated into network attributes like message Time to Live (TTL), routing protocol, and network trigger. The result of that work is an application classification taxonomy based completely on network attributes. This way 7 application classes (like event-driven broadcast and scheduled broadcast) were identified, as shown in Figure 2.1. While this systematic approach is definitely the way to go in order to categorize VANET applications and to map them onto communication patterns, it lacks the grouping by purpose/benefit feature like other approaches do. Additionally, the application communication range requirements were not considered in that analysis, which is of eminent importance for the selection of a specific communication protocol. Moreover, it would be beneficial to analyze more applications that way, not only a few selected ones.

## 2.3 Application Requirements

As we have seen, the envisioned applications are the main driving force behind VANETs. Therefore, we analyze them according to their requirements for the communication system.

Afterwards, we can provide a classification of information dissemination protocols based on network characteristics deduced from application requirements. Before describing these applications, we need to define a set of requirements which influences the selection of the dissemination protocol for an application. These attributes are listed in Table 2.3 and detailed in the following.

| **Requirement** | **Description** | **Choices** |
|---|---|---|
| *Communication Participants* | Who are the communication participants (source and destination) of messages transmitted by the applications? | V2V, I2V, V2I, V2X |
| *Dissemination Range* | How far does the information need to be disseminated by the application? | Short, Medium, Long |
| *Allowable Latency* | What is the maximum allowable delay of information dissemination? | Low, Medium, High |
| *Addressing* | Which destination nodes should receive a message: A single node or all nodes inside a specific region? | Unicast, Multicast |
| *Directionality* | Are sender and receiver establishing a dialogue or is it a pure fire and forget message? | One-way, or Two-way communication |
| *Transmission Trigger* | How are the messages triggered? | Event-driven, Periodic, User-initiated |
| *Information Accuracy* | Accuracy of the received information. | Atomic, Aggregated |

Table 2.3: List of VANET application requirements.

### 2.3.1 Communication Participants

Some applications rely on the availability of infrastructure in order to be functional. Examples are Road Side Units (RSUs) which provide valuable information for the driver, e.g. about road conditions and other dangerous situations. Other applications are designed to function above pure vehicle-to-vehicle communications. Depending on the communication participants, we can distinguish the following cases:

- *V2V:* The communication takes place entirely between vehicles. No infrastructure is involved.

- *I2V:* A RSU is sending information to surrounding vehicles. The vehicles can also further relay the messages through V2V communication to extend the range of the RSU.

- *V2I:* A vehicle directly communicates with a RSU, e.g. for requesting some services.

- *Vehicle-to-Vehicle/Vehicle-to-Infrastructure (V2X):* A hybrid communication scheme including V2V as well as V2I and I2V communications.

### 2.3.2 Dissemination Range

Different applications require different communication ranges. For a Cooperative Collision Warning (CCW) application, e.g. a few hundred meters of communication range are enough. This application exchanges position and velocity information between adjacent vehicles. If these information are exchanged without a significant delay, then the driver can be warned in time. For this application an extended communication range would not enhance the safety, because a potential collision cannot be detected in large distances. Thus, increasing the communication range would not necessarily result in additional benefit regarding safety.

On the other hand, there are applications which inform a driver about a dangerous situation, e.g. an accident ahead. For this purpose a longer communication range would be preferable, thus the driver has more time to react.

There are also applications which need even longer communication distances. Applications, e.g. which gather traffic information of road segments to make a forecast about the estimated travel time would need a communication range of several kilometers. For a driver on a highway it would be important to be warned about a traffic jam as soon as possible to have the chance to take alternative routes.

Therefore, we differentiate three range categories:

- *Short communication range:* Information is disseminated only in the vicinity of a node. Typically in the range of a few hundred meters.

- *Medium communication range:* A maximum dissemination range of few kilometers.

- *Long communication range:* This is the upper limit realizable through vehicular communication, up to several kilometers.

### 2.3.3 Allowable Latency

This specifies the allowable delay introduced by the communication system, defined as the time duration between ready for transmission and the reception of an information. Safety applications have generally much tighter latency requirements onto the communication system than business/entertainment applications. We group the latency requirement into three categories:

- *Low:* The application requires a very fast, i.e. with low latency, dissemination of the information. For applications with a low latency requirement we set the maximum allowed delay to 500 ms.
- *Medium:* This group is for applications with a latency requirement of around one second, thus we set the maximum allowed delay to 1500 ms.
- *High:* All other applications with a relaxed latency requirement, typically in the range of several seconds.

### 2.3.4 Addressing

Depending on the applications, a message needs either to reach exactly one node or a set of nodes. Basically there are two addressing schemes:

- *Unicast:* A node sends a message exactly to one destination node.
- *Multicast:* A message originator sends a messages to a group of nodes.

Multicast group membership can be defined as a location inside a geographic region: All adjacent cars (i.e. located in the area within communication range) or all cars located in geographic region as defined in a message, e.g. a road segment behind the vehicle.

### 2.3.5 Directionality

Two communication directionalities can be distinguished:

- *One-way communication:* This means that a source node sends a message without expecting a reply. It happens in a fire and forget manner: there is no acknowledgement of that message, thus the sender has no knowledge whether the message was received or not.
- *Two-way communication:* The other possibility is that a source node establishes a dialogue with a destination node, i.e. the destination sends a response message.

Typically unicast communication make use of two-way-communication because several messages are exchanged during the same connection. Multicast applications usually use one-way-communication because it is sufficient for the most use-cases and it would be costly – in terms of communication overhead – to realize two-way communication (which includes acknowledgements) in multicast groups.

### 2.3.6 Transmission Trigger

Different applications require different triggering mechanisms for message transmission. For example, a CCW application needs the periodic exchange of information between vehicles. On the other hand, other applications trigger a message transmission as a result of an event. For example, the detection of a collision with another vehicle could trigger the immediate transmission of a warning message. Also a user can trigger the transmission of messages. For example, by querying traffic information in a specific road segment or by initiating a message chat with a passenger in another vehicle.

This requirement defines three possibilities of how a message transmission is triggered:

- *Event-driven:* When a special event (e.g. two cars crashed) occurs and other vehicles have to be informed quickly.
- *Periodic:* Applications generate the messages at regular intervals, e.g. for monitoring vehicles in the neighborhood.
- *User-initiated:* A user initiates a message transmission, e.g. by querying traffic information in a distant region.

It is important to note that this attribute defines the initial transmission. For example, an application transmits a message on an event occurrence (such as a breakdown of a vehicle) to warn other participants, but after that this warning has to be maintained until the dangerous situation ends. Such a maintenance can be achieved by a periodic repetition of the message (in the case that the situation is bound to a vehicle) or through store and forward mechanism which retransmits a message if new vehicles are in communication range.

### 2.3.7 Information Accuracy

A vehicle can transmit an information either unchanged – i.e. the original value is transmitted – or a new value is calculated based on other information received from other vehicles or gained from own sensors. Therefore, there are two categories of information accuracy we distinguish:

- *Atomic:* Applications like CCW require the exact position, heading, and velocity of neighboring vehicles. The application needs the original, unchanged values in order to being able to calculate a precise collision probability.

- *Aggregated:* If an application wants to determine the average travel time on a highway segment of a few kilometers length, then one aggregated, average value is sufficient. If vehicles already have determined the average velocity on that segment (using a certain aggregation function), only one message is enough to inform the querying vehicle. On the other hand, the querying vehicle would not have a higher benefit if all vehicles in the requested segment transmitted their atomic velocities. With $n$ vehicles on that segments $n$ messages were needed to gather all atomic information. Regarding the bandwidth limit, it would be unwise doing so.

## 2.4 Classification of VANET Applications

The task 3 final report of the VSC project [2] serves as the main source for the applications listed in this section. Further sources for this compilation are applications classified from a network perspective from Bai et al. in [3], the applications listed by Dötzer er al. in [5], furthermore, applications discussed in [13, 4]. Moreover, also query-based VANET applications as found in [14, 15, 16, 17, 18] are considered.

As already mentioned, we want to achieve a purpose-based classification combined with application requirements. To achieve this, we first sort the applications by the basic benefit oriented classes introduced by Schoch et al. in [4]. After that, we characterize the applications by the requirements described in Section 2.3. This evaluation reveals, that the communication requirements dissemination range and latency are one of the key requirements which can be used to organize the applications into subclasses.

The result of this approach is shown in Figure 2.2. The figure shows those application classes and their interrelation to the two mentioned requirements. In the following subsections this classification is described in detail. I.e., each application class is detailed in three parts:

1. First, the common requirements of an application class are listed in a table. Requirements which differ from application to application are not shown, but are detailed in the next two steps.

2. Second, a short description for each application of a class is given, outlining their individual characteristics.

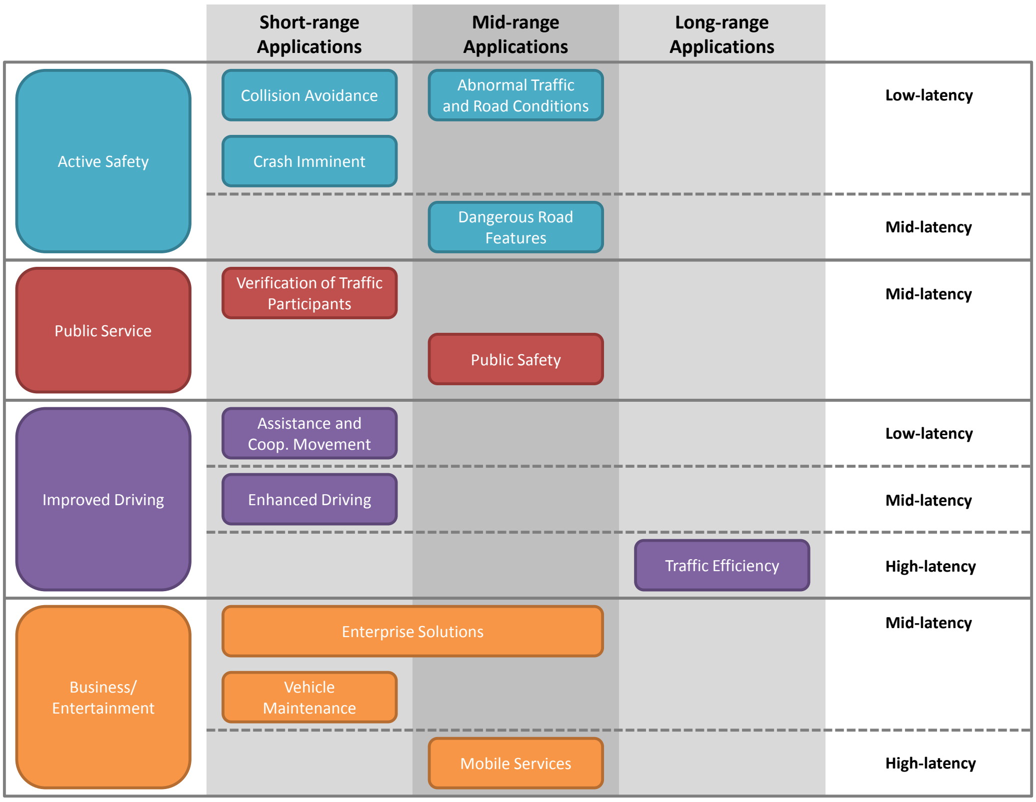


Figure 2.2: Classification of VANET applications based on application range, allowed latency, and purpose.

3. Third, the individual requirements of each application are summarized in a table.

Note, that this way, the number of rows of the first table and the number of columns of the second table vary, depending on how many requirements applications of a class have in common.

### 2.4.1 Active Safety Applications

Active safety applications represent the most important group of VANET applications. The goal of these applications is to reduce the number of injuries and fatalities caused in traffic accidents. In the European Union (EU27) e.g., more than 1.2 million traffic accidents involved injury of passengers in 2007 and more than 42,000 accidents ended fatal [19]. Hence, there is a high potential benefit in the implementation of such applications [2]. To achieve this goal, safety applications disseminate information about hazardous situations (e.g. about abnormal road conditions or post-crash warning) to vehicles which can benefit from such information to avoid an accident.

Application Safety is the base group of all these safety related applications. There is a huge amount of such applications, thus for being able to regard them more differentiated, the grouping of those applications into subgroups is needed. Therefore, based on the analysis of the application requirements, the following subclasses were identified: *Collision Avoidance*, *Crash Imminent*, *Dangerous Road Features*, and *Abnormal Traffic and Road Conditions*. These groups are detailed in the following.

#### Collision Avoidance

These applications intend to avoid the collision of vehicles by immediately warning the driver if such a dangerous situation occurs in the direct vicinity. Such situations occur, e.g. when a driver violates a traffic signal or a stop sign, or a driver ignores someone's right of way, and other dynamic traffic situations where vehicle collisions can occur.

Besides the attribute *communication participants*, these types of applications have in common all other communication characteristics described in Section 2.3. This is summarized in Table 2.4 and described in the following. The most important characteristic is that they rely on short-range communication, i.e. information gathered from vehicles or RSUs in the range of few hundred meters. It makes no sense to include information from vehicles which are located further away because due to the dynamicity of vehicles it cannot be determined if two vehicles will collide if they are distant. Thus, these applications warn the driver shortly before an accident happens, and therefore, the other important classification characteristic is

| **Communication Requirements** | **Value** |
|---|---|
| *Dissemination Range* | Short |
| *Allowable Latency* | Low |
| *Addressing* | Multicast |
| *Directionality* | One-way |
| *Transmission Trigger* | Periodic |
| *Information Accuracy* | Atomic |

Table 2.4: Common communication requirements of Collision Avoidance applications.

the low latency communication requirement. Moreover, all these applications rely on information multicast periodically either by vehicles or RSUs. Also only one-way communication is used and the transmitted information have to be atomic, that is, the values are as they were received by sensors and not averaged or aggregated by other means.

| **Acronym** | **Application** | **Comm. Part.** |
|---|---|---|
| *TSVW* | Traffic Signal Violation Warning | I2V |
| *SSVW* | Stop Sign Violation Warning | I2V |
| *BSW* | Blind Spot Warning | V2V |
| *LCW* | Lane Change Warning | V2V |
| *ICW* | Intersection Collision Warning | I2V |
| *CCW* | Cooperative Collision Warning | V2V |
| *WAPC* | Warning About Pedestrians Crossing | I2V |
| *RCW* | Rail Collision Warning | V2V or I2V |

Table 2.5: List of Collision Avoidance applications and their different network characteristics.

The information needed by an application for being able to recognize such dangerous situations can be provided either by V2V or I2V communications. Based on this differentiation, these applications can be further divided into *cooperative* and *infrastructure-based* applications.

- *Cooperative Applications:* The information used by the application is based on messages received from other vehicles. Vehicles gather data about their own dynamics like position, heading, velocity, acceleration, and yaw rate. This information is periodically multicast to the neighboring vehicles. This way all vehicles have up-to-date and exact information of vehicles in their vicinity, thus the probability of a collision can be calculated and the driver informed (see [20] for details). Example applications are CCW, Lane Change Warning (LCW), and Blind Spot Warning (BSW).

- *Infrastructure-based Applications:* This sort of applications relies on information periodically multicast by RSUs. Such infrastructure can be used at hot-spots like intersections (for Intersection Collision Warning (ICW) and Stop Sign Violation Warning (SSVW) applications), at pedestrian crossings to implement a Warning About Pedestrians Crossing (WAPC) application, or at traffic signals to realize a Traffic Signal Violation Warning (TSVW) application.

A Rail Collision Warning (RCW) application can be implemented as both, cooperative and infrastructure-based application. In the first case the train is equipped with a wireless communication unit and broadcasts periodically its position. The vehicles can calculate the probability for a collision based on their own and the trains' position, and warn the driver if necessary. The second possibility is to use a RSU near a railway crossing which senses an approaching train and warns vehicles in its proximity if needed. From an economic perspective the first realization would be more beneficial, because significantly less communication devices are needed.

A list of Collision Avoidance applications is shown in Table 2.5. This table also includes the communication participants attribute which differs from application to application as discussed.

### Crash Imminent

| Communication Requirements | Value |
|---|---|
| *Communication Participants* | V2V |
| *Dissemination Range* | Short |
| *Allowable Latency* | Low |
| *Addressing* | Unicast |
| *Directionality* | Two-way |
| *Transmission Trigger* | Event-driven |
| *Information Accuracy* | Atomic |

Table 2.6: Common communication requirements of Crash Imminent applications.

These applications apply to situations with unavoidable, imminent collisions. This can happen for example when two cars are separated by an obstacle, thus no communication is possible between them. When they pass this obstacle, the distance between them could be already too close, thus the accident is unavoidable [21].

Although there is only a very short time until the collision happens, the exchange of information between the cars participating in the imminent collision could be highly beneficial. Such information could be used by a Pre-Crash Sensing (PCS) application for the preparation of passive safety systems, e.g. to fasten the seat belts, prepare emergency brake assist, and bumper extension for increased frontal crush zone [2].

This is the only application of the Crash Imminent class we found in the literature, and for the sake of completeness this application is listed in Table 2.7.

| **Acronym** | **Application** |
|---|---|
| *PCS* | Pre-Crash Sensing |

Table 2.7: List of Crash Imminent applications.

Characteristic for this application is a short communication range, and especially a very low latency requirement. The PCS application uses two-way point-to-point communication transmitting atomic application data. The transmission trigger is event-based, i.e. in the case of an imminent collision the two cars exchange the needed information. These requirements are summarized in Table 2.6.

#### Dangerous Road Features

| **Communication Requirements** | **Value** |
|---|---|
| *Communication Participants* | I2V and V2V |
| *Dissemination Range* | Medium |
| *Allowable Latency* | Medium |
| *Addressing* | Multicast |
| *Directionality* | One-way |
| *Transmission Trigger* | Periodic |
| *Information Accuracy* | Atomic |

Table 2.8: Common communication requirements of Dangerous Road Features applications.

This group of applications is based on infrastructure installed at dangerous road places. They periodically broadcast warning messages to nearby vehicles about the dangerous features they were installed for. An example is the Curve Speed Warning (CSW) application which informs approaching vehicles about the exact position of the dangerous curves with additional attributes like curve speed limit, and curvature. The application can decide based on the data received and it's own sensor information if the driver needs to be informed. Another examples are Work Zone Warning (WZW) application which informs the driver about the position, extent, and speed limit of a construction zone, and further applications which warn the driver about insufficient height on the road like Low Bridge Warning (LBW) and Low Parking Structure Warning (LPSW).

| **Acronym** | **Application** |
|---|---|
| *CSW* | Curve Speed Warning |
| *LPSW* | Low Parking Structure Warning |
| *LBW* | Low Bridge Warning |
| *WZW* | Work Zone Warning |

Table 2.9: List of Dangerous Road Features applications.

All these applications share the same communication requirements, which are summarized in Table 2.8. The main difference to the other safety applications previously examined is that a medium latency requirement suffices for these applications. Another difference is that these applications benefit from a larger dissemination range which can be realized by additionally using V2V communications. Therefore, they are categorized with a medium dissemination range requirement. Possible applications of this class are listed in Table 2.9.

#### Abnormal Traffic and Road Conditions

| **Communication Requirements** | **Value** |
|---|---|
| *Dissemination Range* | Medium |
| *Allowable Latency* | Low |
| *Addressing* | Multicast |
| *Directionality* | One-way |
| *Transmission Trigger* | Event-driven |
| *Information Accuracy* | Atomic |

Table 2.10: Common communication requirements of Abnormal Traffic and Road Conditions applications.

There is a wide range of applications which intend to warn drivers upon the occurrence of an abnormal condition, be it a road condition or a dangerous traffic situation. The essence of these applications is to quickly inform approaching vehicles if such an abnormal condition event occurs. The typical dissemination range is several hops. With this enhanced dissemination range vehicles are able to receive the warning earlier. The benefit hereof is that a driver has more time to react. This, possibly allows him to avoid a dangerous situation completely. Moreover, if such a message is received in time then the navigation could also re-plan a route, e.g. by receiving the warning of an end of traffic-jam.

| **Acronym** | **Application** | **Comm. Part.** |
|---|---|---|
| *EEBL* | Emergency Electronic Brake Lights | V2V |
| *SSVA* | Stopped or Slow Vehicle Advisor | V2V |
| *WWDW* | Wrong Way Driver Warning | V2V |
| *IRCW* | Infrastructure-based Road Condition Warning | I2V |
| *VRCW* | Vehicle-based Road Condition Warning | V2V |
| *PCW* | Post-Crash Warning | V2V |
| *BW* | Breakdown Warning | V2V |
| *VVRFN* | Vehicle-to-Vehicle Road Feature Notification | V2V |
| *ETJW* | End of Traffic Jam Warning | V2V |

Table 2.11: List of Abnormal Traffic and Road Conditions applications and their different network characteristics.

These warning messages are sent one-way to a group of nodes (multicast addressing). The group membership of these addressed nodes is typically based on a geographic region, thus Geographic Broadcast (GeoCast) is the typical protocol used to disseminate the information. After such an event occurred and the first warning was transmitted, the information has to be held up to date over time. Although these protocols are classified as event-triggered applications, the message can be resent periodically until the situation is cleared.

Examples of this type of applications are the already mentioned End of Traffic Jam Warning (ETJW) application and the Emergency Electronic Brake Lights (EEBL) application which informs approaching vehicles to avoid a rear end collision. The Post-Crash Warning (PCW), Stopped or Slow Vehicle Advisor (SSVA), and the Breakdown Warning (BW) applications inform arriving vehicles about the own situation. This way arriving drivers are warned in time. The Vehicle-based Road Condition Warning (VRCW) and the Vehicle-to-Vehicle Road Feature Notification (VVRFN) applications use sensors to detect abnormal road conditions (like e.g. an icy road) or dangerous road features (such as grade, curve, etc. which exceed a certain limit), and warn other vehicles by a broadcast of those information.

Finally, the Wrong Way Driver Warning (WWDW) application can advise oncoming traffic to avoid accidents in this hazardous situation.

These applications use solely V2V communication, except the Infrastructure-based Road Condition Warning (IRCW) application uses infrastructure-based communication. The common communication attributes of these applications is summarized in Tabel 2.10 and the list of applications can be found in Table 2.11.

### 2.4.2 Public Service Applications

One goal of VANET applications is to facilitate the operation of public institutions and authorities such as police departments, fire departments etc. There are several public service applications which intend to accomplish this task. The idea is that vehicles of such institutions equipped with an On Board Unit (OBU) can query information about vehicles, or disseminate warning messages in the case of an emergency. Furthermore, also infrastructure can be used to support the authorities by the dissemination of important information to vehicles on the roads.

Based on the communication characteristics, two different public service application types can be distinguished: *Verification of Traffic Participants* and *Public Safety*. These application groups are detailed in the following.

#### Verification of Traffic Participants

| **Communication Requirements** | **Value** |
|---|---|
| *Communication Participants* | V2V |
| *Dissemination Range* | Short |
| *Allowable Latency* | Medium |
| *Addressing* | Unicast |
| *Directionality* | Two-way |
| *Transmission Trigger* | User-initiated |
| *Information Accuracy* | Atomic |

Table 2.12: Common communication requirements of Verification of Traffic Participants applications.

*Verification of Traffic Participants* applications typically use two-way unicast communication to an established connection between the public service car and another vehicle. This connection is used to gain information from that car, which can be used by the authorities e.g. to verify the driver. This communication is triggered by a user (the authorities), and atomic data over a short communication range are exchanged.

Example applications are Electronic Drivers License (EDL) which can be used by a police patrol to remotely check the validity of the driver's license of the operator of an examined car, Electronic License Plate (ELP) to determine the identity of a car and the vehicle owner, and to perform a Vehicle Safety Inspection (VSI).

| **Acronym** | **Application** |
|---|---|
| *ELP* | Electronic License Plate |
| *EDL* | Electronic Drivers License |
| *VSI* | Vehicle Safety Inspection |

Table 2.13: List of Verification of Traffic Participants applications.

These applications share the same common communication attributes as outlined in Table 2.12. The described applications are listed in Table 2.13.

### Public Safety

| **Communication Requirements** | **Value** |
|---|---|
| *Dissemination Range* | Medium |
| *Allowable Latency* | Medium |
| *Information Accuracy* | Atomic |

Table 2.14: Common communication requirements of Public Safety applications.

Public services vehicles participate in road traffic and even more important, such a vehicle being on duty results frequently in exceptional situations. In such cases it would be profitable to disseminate warning messages to the ordinary vehicles in order to alert the driver about the extraordinary situation. Other use-cases are when a driver or other person needs the help from the public authorities.

There are several public safety applications, which are briefly described in the following. A summary of these applications can be found in Table 2.15. An Approaching Emergency Vehicle Warning (AEVW) could disseminate messages into a geographic area ahead on the route of the emergency vehicle to request right of way in that area. It is important to inform driver in time, enabling them to make e.g. room for the approaching vehicle. Furthermore, the right of way could also be requested by emergency vehicles from traffic signals in travel di-

| Acronym | Application | Part. | Addr. | Direct. | Trigger |
|---|---|---|---|---|---|
| *AEVW* | Approaching Emergency Vehicle Warning | V2V | Multicast | One-way | Event-driven |
| *EVSW* | Emergency Vehicle at Scene Warning | V2V | Multicast | One-way | Periodic |
| *SOSS* | SOS Service | V2X | Multicast | One-way | Event-driven |
| *EVSP* | Emergency Vehicle Signal Preemption | V2I | Unicast | Two-way | Event-driven |
| *IVAA* | In-Vehicle Amber Alert | I2V | Multicast | One-way | Periodic |
| *SVT* | Stolen Vehicles Tracking | V2X | Multicast | One-way | Periodic |

Table 2.15: List of Public Safety applications and their different network characteristics.

rection by using an Emergency Vehicle Signal Preemption (EVSP) application. Additionally, if such an emergency vehicle arrives at a scene, then approaching vehicles could be warned by periodically sending messages through an Emergency Vehicle at Scene Warning (EVSW) application.

Further applications are the use of SOS Service (SOSS) by vehicles in emergency situations, e.g. after an accident. Such an application could use V2X communications to request assistance from local authorities. Another application is the In-Vehicle Amber Alert (IVAA) which make use of infrastructure to disseminate this alert to the vehicles. Depending on the deployed density of RSUs, also V2V can be used to enhance the dissemination range. Furthermore, in the case of car theft, the Stolen Vehicles Tracking (SVT) application can be used for tracking.

As shown in Table 2.14, the common communication characteristics of these applications are the communication range, latency, and the accuracy of the transmitted information. The discussed applications are listed in Table 2.15, together with their individual communication characteristics.

### 2.4.3 Improved Driving Applications

These kind of applications intend to improve the driving efficiency and comfort on roads by means of communications. They can assist the driver performing difficult maneuvers, enhance the driving by the utilization of information received from other cars and RSUs, and optimize the traffic flow on roads, i.e. minimizing the travel time, by disseminating and processing information of traffic and road conditions.

These applications could make driving more convenient and efficient. Convenient applications usually use short-range communication and they can be further differentiated based on their latency requirements. *Assistance and Cooperative Movement* applications have low communication latency requirements, whereas for *Enhanced Driving* applications a medium latency is adequate. On the other hand, *Traffic Efficiency* applications typically require a long communication range in order to being able to fulfill their tasks. This implies a more relaxed communication latency requirement, because the dissemination of information introduces automatically additional delay over multiple hops in a region of several kilometers.

These three *Improved Driving* application classes are detailed in the following, along with the applications of each class and their communication requirements.

### Assistance and Cooperative Movement

These applications assist by performing difficult tasks during driving. Therefore, they monitor the surroundings of a vehicle and detect the maneuvers a driver is executing by processing their own sensor data. If certain situations are detected, the application actively assists the driver, for instance by displaying some information like a stop sign. Without this assistance, the situation quickly could turn into a dangerous one, e.g. a possible collision.

| **Communication Requirements** | **Value** |
|---|---|
| *Dissemination Range* | Short |
| *Allowable Latency* | Low |
| *Addressing* | Multicast |
| *Directionality* | One-way |
| *Transmission Trigger* | Periodic |
| *Information Accuracy* | Atomic |

Table 2.16: Common communication requirements of Assistance and Cooperative Movement applications.

Therefore, these applications have low latency and short communication range requirements. Furthermore, they rely on atomic information periodically disseminated to adjacent vehicles. Thus, theses applications use one-way multicast communication. These common communication parameters are summarized in Table 2.16.

Several applications belong to this class. For instance a Blind Merge Assistant (BMA) can be used to assist the driver merging from a location with limited visibility. A RSU placed on such locations is in view of the merging vehicle and the vehicles on the main road. Thus, the

| Acronym | Application | Part. |
|---|---|---|
| *BMA* | Blind Merge Assistant | V2X |
| *HMA* | Highway Merge Assistant | V2V |
| *LTA* | Left Turn Assistant | V2V |
| *SSMA* | Stop Sign Movement Assistance | V2V |
| *VE* | Visibility Enhancer | V2V |
| *CACC* | Cooperative Adaptive Cruise Control | V2V |
| *CVHAS* | Cooperative Vehicle-Highway Automation System (Platoon) | V2V |

Table 2.17: List of Assistance and Cooperative Movement applications and their different network characteristics.

RSU is able to provide information to the cars, which is then processed by the application and displayed to the driver. The Highway Merge Assistant (HMA) is using V2V communication to periodically exchange position, velocity, and other data between vehicles in order to aid the driver during the merging maneuver. In similar way a Left Turn Assistant (LTA) can be realized, which provides the driver with information about oncoming traffic, and in the case that the left turn is safe by giving an appropriate signal. Analog to the LTA, a Stop Sign Movement Assistance (SSMA) can be implemented. Furthermore, a Visibility Enhancer (VE) application can be used to display surrounding vehicles, to assist the driver in cases where the visibility is limited. Also applications like Cooperative Adaptive Cruise Control (CACC) and Cooperative Vehicle-Highway Automation System (Platoon) (CVHAS) can be realized based on V2V communication to provide the driver advanced cruise control (e.g. intelligent speed adaptation) features and driving in a platoon.

These applications – and their specific communication requirements – are listed in Table 2.17.

#### Enhanced Driving

This is a group of a few applications which enhance the driving on roads. For example, using the high-beams at night can disturb oncoming traffic. In the worst case, this can also lead to accidents which could be avoided by the Cooperative Glare Reduction (CGR) application. Vehicles use therefore short-range V2V communication to periodically exchange information about the own position and the vehicle dynamics. Using these information, this application switches automatically to low-beams if is reasonable.

Another scope of application is the displaying of road signs in the car. This In-Vehicle

| **Communication Requirements** | **Value** |
|---|---|
| *Dissemination Range* | Short |
| *Allowable Latency* | Medium |
| *Addressing* | Multicast |
| *Directionality* | One-way |
| *Transmission Trigger* | Periodic |
| *Information Accuracy* | Atomic |

Table 2.18: Common communication requirements of Enhanced Driving applications.

Signage (IVS) application retrieves these information from RSUs which periodically broadcast sign information in their proximity. Example sign information are school zone warnings, animal crossing warnings etc. By using such a service also excessive road signing could be avoided, by displaying only the relevant ones. Moreover, unreadable signs would not represent a problem anymore. Such an application would be a nice feature for drivers, and definitely making driving more convenient.

| **Acronym** | **Application** | **Part.** |
|---|---|---|
| *CGR* | Cooperative Glare Reduction | V2V |
| *IVS* | In-Vehicle Signage | I2V |
| *ADM* | Adaptive Drivetrain Management | I2V |

Table 2.19: List of Enhanced Driving applications and their different network characteristics.

Finally, Adaptive Drivetrain Management (ADM) is another example for a nice to have application for VANETs. For this application also a RSU is used, to broadcast information about road features such as grades and curves. This information could be used to anticipate shift patterns, resulting in a reduction of the fuel consumption.

The described common communication requirements of these applications can be found in Table 2.18. For the list of applications and their specific communication attributes refer to Table 2.19.

### Traffic Efficiency

Traffic Efficiency applications intend to optimize the traffic flow on roads, i.e. minimizing the travel time by disseminating information about traffic flow conditions. Therefore, cars periodically exchange and combine information received from neighboring vehicles with data sensed by own sensors, aggregate them, and disseminate the newly gathered information for other vehicles.

This way, applications like a Cooperative Traffic Jam Detection (CTJD) or Intelligent Traffic Flow Control (ITFC) can be realized. A driver having e.g. information about a traffic jam in advance, could choose an alternative route (with the assistance of the car navigation system), reducing the travel time. A successful deployment of such applications could greatly reduce the fuel consumption of vehicles, which would have a great impact on cost reduction as well as on the reduction of $CO_2$ emission.

| **Communication Requirements** | **Value** |
|---|---|
| *Communication Participants* | V2X |
| *Dissemination Range* | Long |
| *Allowable Latency* | High |
| *Addressing* | Multicast |
| *Directionality* | One-way |
| *Information Accuracy* | Aggregated |

Table 2.20: Common communication requirements of Traffic Efficiency applications.

Such aggregated information – and other information gathered from sensors or received from other vehicles – could also be sent by a Notification of Road Conditions to a Traffic Operation Center (NCTOC) application to a Traffic Operating Center (TOC). Based on information gathered this way, RSUs could redistribute processed traffic information to realize an Enhanced Route Guidance and Navigation (ERGN) application. Another example for the dissemination of aggregated information over large distances is a Parking Places Locator Service (PPLS) application.

The *Traffic Efficiency* applications discussed so far are periodical. Also user-initiated applications of this type do exist. These are query-based applications, i.e. a user triggers the application by requesting a remote information through transmitting a query. The query is transported hop by hop to the destination, and there the response is determined and transported back to the query initiator. Examples are a Query-based Parking Places Locator Service (QPPLS) which allows the querying of accurate parking place information in distant regions, and a Traffic Information Query (TIQ) which provides accurate traffic information from distant regions. The difference to their periodic counterpart is that the accuracy of the retrieved information is not dependant on the distance between source and destination.

These applications are delay-tolerant, i.e. they do not impose such tight time constraints

| Acronym | Application | Trigger |
|---|---|---|
| *CTJD* | Cooperative Traffic Jam Detection | Periodic |
| *ITFC* | Intelligent Traffic Flow Control | Periodic |
| *NCTOC* | Notification of Road Conditions to a Traffic Operation Center | Periodic |
| *ERGN* | Enhanced Route Guidance and Navigation | Periodic |
| *PPLS* | Parking Places Locator Service | Periodic |
| *QPPLS* | Query-based Parking Places Locator Service | User-initiated |
| *TIQ* | Traffic Information Query | User-initiated |

Table 2.21: List of Traffic Efficiency applications and their different network characteristics.

as safety applications, but mostly need to exchange information over long distances. The common requirements are shown in Table 2.20. The application list with the specific requirements can be found in Table 2.21.

### 2.4.4 Business/Entertainment Applications

This type of applications is neither safety-related nor intends to make driving more efficient. They provide solutions for different stakeholders, they provide e.g. payment services and different commercial applications for enterprises, vehicle maintenance solutions for car manufacturers, and mobile services for driver and passengers. This type of applications is covered in the following.

#### Enterprise Solutions

These applications are targeting enterprises to facilitate some services they can use to carry out their business. Typically these applications require unicast, two-way communication of atomic information with a medium transmission latency requirement. Such applications can use e.g. I2V and V2I short-range communication to provide E-Payment (EPay) services such as toll collection, parking payment, gas payment, etc. With the same infrastructure and wireless communication mechanisms an Area Access Control (AAC) application can be used by an enterprise to provide automatic access control to a property. The Rental Car Processing (RCP) application automates some processes such as access to a car or the automatic registration on return of the rented car. Another example for a short-range application example is the event-driven Parking Spot Locator (PSL) application which guides the driver to a free parking slot.

| **Communication Requirements** | **Value** |
|---|---|
| *Allowable Latency* | Medium |
| *Addressing* | Unicast |
| *Directionality* | Two-way |
| *Information Accuracy* | Atomic |

Table 2.22: Common communication requirements of Enterprise Solutions applications.

Furthermore, there are several middle range applications such as Fleet Management (FM), based on V2X communication, and a Hazardous Material Cargo Tracking (HMCT) to allow a company to monitor the transportation of such cargo and thus to improve safety.

| **Acronym** | **Application** | **Part.** | **Range** | **Trigger** |
|---|---|---|---|---|
| *EPay* | E-Payment | V2I, I2V | Short | User-initiated |
| *AAC* | Area Access Control | V2I, I2V | Short | User-initiated |
| *RCP* | Rental Car Processing | V2I, I2V | Short | User-initiated |
| *PSL* | Parking Spot Locator | V2I, I2V | Short | Event-driven |
| *FM* | Fleet Management | V2X | Medium | Periodic |
| *HMCT* | Hazardous Material Cargo Tracking | V2X | Medium | Periodic |

Table 2.23: List of Enterprise Solutions applications and their different network characteristics.

As we have seen, the most decisive communication characteristics for this type of applications is the point-to-point unicast communication with a medium communication latency requirement. These common attributes are shown in Table 2.22, while the specific requirements are shown in the application list in Table 2.23.

### Vehicle Maintenance

The second group of *Business/Entertainment* applications applies to car manufacturers as stakeholder, as these applications provide vehicle maintenance services for their customer. Typically, they use deployed infrastructure and, depending on the application, they are event-driven or user-initiated. A short communication range is adequate for these applications and point-to-point unicast communication with medium latency requirements. These communication attributes are listed in Table 2.24.

| Communication Requirements | Value |
|---|---|
| *Dissemination Range* | Short |
| *Allowable Latency* | Medium |
| *Addressing* | Unicast |
| *Directionality* | Two-way |
| *Information Accuracy* | Atomic |

Table 2.24: Common communication requirements of Vehicle Maintenance applications.

| Acronym | Application | Part. | Trigger |
|---|---|---|---|
| *WD* | Wireless Diagnostics | I2V | User-initiated |
| *SUF* | Software Update/Flashing | I2V | User-initiated |
| *RVP* | Remote Vehicle Personalization | I2V | User-initiated |
| *JIRN* | Just-in-Time Repair Notification | I2V,V2I | Event-driven |
| *SRN* | Safety Recall Notice | V2I | Event-driven |

Table 2.25: List of Vehicle Maintenance applications and their different network characteristics.

In the following examples of applications of this group are discussed, which are listed in Table 2.25. By the Wireless Diagnostics (WD) and Software Update/Flashing (SUF) services a car can be remotely checked and also updated. Thus, these applications could be used in car workshop to alleviate the time and effort needed for these processes by contrast with present-day wired-based diagnostics. These two applications are user-initiated – by the motor mechanic – together with the Remote Vehicle Personalization (RVP) application, where the car can be personalized through I2V communications according to the driver preferences.

There are also event-driven applications which also use short-range unicast communication. The Just-in-Time Repair Notification (JIRN) application uses V2I and I2V communication to enable a car to request assessment from a technical support center. Therefore, the car transmits e.g. an error code, which is used by the support center to determine the cause and where and how the driver can be assisted. Also a Safety Recall Notice (SRN) application can be realized this way, by a RSU sending such notifications to bypassing cars. An alternative implementation of this application would be the use of a multi-hop broadcast instead of unicast communication (in [2] unicast is assumed whereas in [4] broadcast is used). The advantage of the unicast approach is that the number of messages are significantly reduced in comparison with the second approach. A notification is only sent if a car in question is located in communication range of the RSU. On the other hand, the second approach has a much greater range, thus it can be also used in sparsely deployed RSU environments.

### Mobile Services

| **Communication Requirements** | **Value** |
|---|---|
| *Communication Participants* | V2X |
| *Dissemination Range* | Medium |
| *Allowable Latency* | High |
| *Information Accuracy* | Atomic |

Table 2.26: Common communication requirements of Mobile Services applications.

These applications supply business and entertainment services for the driver and passengers. For instance, through an Instant Messaging (IM) application car occupants could exchange textual information with persons in other cars. Furthermore Internet Service Provisioning (ISP) would allow to access the internet and to check email. Also a Map Download/Update (MDU) application would be a nice to have feature, by enabling vehicles to automatically download maps or update their map database. Finally, Point-of-Interest Notification (PoIN) could be used to inform travelers by wireless communication about local attractions and services, e.g. a gas station could advertise its prices.

| **Acronym** | **Application** | **Addr.** | **Direct.** | **Trigger** |
|---|---|---|---|---|
| *IM* | Instant Messaging | Unicast | Two-way | User-initiated |
| *ISP* | Internet Service Provisioning | Unicast | Two-way | User-initiated |
| *MDU* | Map Download/Update | Unicast | Two-way | User-initiated |
| *PoIN* | Point-of-Interest Notification | Multicast | One-way | Periodic |

Table 2.27: List of Mobile Services applications and their different network characteristics.

These applications typically use unicast communication, except PoIN, which uses multicast communication to inform all nearby vehicles. Furthermore, the common communication criteria are middle range communication of atomic information with high latency requirements, as shown in Table 2.26. The discussed applications are listed in Table 2.27.

## 2.5 Summary

In this chapter we examined the envisioned applications for VANETs. Because there are a plenty of applications with diverse purposes and different communication requirements, the main contribution of this chapter was the establishment of a taxonomy based on those criteria. By using such a taxonomy similar applications can be evaluated uniformly from a communication perspective, thus reducing the complexity significantly.

To accomplish this objective, we first reviewed the literature in Section 2.2 for existing research conducted on this field. The results were used as a base for our work and to assemble the communication requirements of VANET applications in Section 2.3. These requirements were applied to define the communication attributes of the applications. Furthermore, based on these attributes and the purpose of applications we succeeded to provide a systematic classification of VANET applications in Section 2.4.

On the basis of these results, we can survey and evaluated the different vehicular communication mechanisms and patterns. In the next chapter we are analyzing which communication mechanism can be used for which application class to optimally fulfill the application requirements.

# CHAPTER 3

# Vehicular Communications

The main objective of this chapter is to give an introduction to vehicular communication, to identify the building blocks for information dissemination in Vehicular Ad-hoc Networks (VANETs) and the vehicular network characteristics together with non-functional requirements of dissemination protocols which are the basis for further evaluation of such protocols. The next section exactly describes the methodology used to achieve these goals.

## 3.1 Methodology

The aim of this chapter is to provide a classification of communication mechanisms based on the requirements derived from the application properties. In the end we want to have a mapping from the application classes acquired in Chapter 2 to a few communication mechanisms which are the building blocks for VANET applications. To achieve this goal, the following steps are carried out in the following sections:

1. **Outline of wireless hardware used**
   In order to being able to discuss and design communication protocols for VANETs, we need to be aware of the hardware and low layer protocols used, and their implications and limitations for the routing layer. Thus, in Section 3.2 the low level communication mechanisms are described.

2. **Overview of vehicular communication**
   In Section 3.3 a basic overview of Inter-Vehicle Communications (IVC) is given and

different VANET scenarios are defined and discussed. Depending on which IVC type is used, this might influence the possible applications which in turn determine the requirements for the communication system.

3. **Mapping of basic communication mechanisms onto application reqirements**
   In a next step, the application requirements compiled in Section 2.3 are mapped according to attributes of the communication mechanisms used for IVC. I.e., by which communication mechanism the communication requirements of an application class can be satisfied optimally. In this process also the implications from the vehicular communication classification are considered. This mapping is described in Section 3.4.

4. **Classification of communication mechanisms**
   Based on the mapping from the last step, a classification of VANET communication mechanisms is accomplished in Section 3.5. They can be regarded as communication patterns, as described by Schoch et al. in [4]. Advanced commincation patterns are defined in Section 3.6.

5. **VANET characteristics and non-functional communication requirements**
   Based on identified communication patterns, we are going to evaluate efficient dissemination protocols in the following chapters. To evaluate these protocols systematically, we first need to identify the specific characteristics of vehicular networks which influence the design of such protocols in Section 3.7. Additionally, non-functional requirements are defined in Section 3.8 which provide the metrics for a quantitative analysis of different information dissemination approaches. These metrics play an important role for the evaluation and the benchmark of different approaches.

## 3.2 Preliminaries

In this section we are looking at the basics of vehicular communications. The aim is to provide an overview over the communication stack and enabling technologies of VANETs. From that, basic communication characteristics and concepts can be derived, which are further used in this chapter to facilitate the connection between application requirements and communication protocols. These are finally used for the classification of vehicular communication mechanisms.

Therefore, we outline in the next subsections the used low layer communication protocols and present their implications onto the higher layer ones. Also the available data in vehicles – be it from own sensors or received from other participants – is briefly discussed in the following.

### 3.2.1 Radio Hardware

Dedicated Short-Range Communications (DSRC) (cf. [22]) is a suite of standards designed to enable low-latency wireless communications of safety and non-safety messages in VANETs [23, 24]. It is an enabling technology for a wide range of applications [25, 26], particularly, DSRC can be used to realize the applications discussed in Chapter 2. It is currently considered as the most promising approach to facilitate Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications [27, 28].

Therefore, the U.S. Federal Communications Commission (FCC) allocated in 1999 a 75 MHz spectrum at 5.9 GHz for the use of intelligent transportation services [29]. This band can be used exclusively for V2V and Infrastructure-to-Vehicle (I2V) communications and is divided into seven 10 MHz wide channels [30]. In Europe, a similar allocation was proposed by the European Telecommunications Standards Institute (ETSI) [31, 32] from which a 30 MHz band from 5.875 to 5.905 GHz was approved by the European Commission in 2008 [33]. These two allocations – from Europe and the U.S. – are depicted in Figure 3.1 according to [27] and [32].

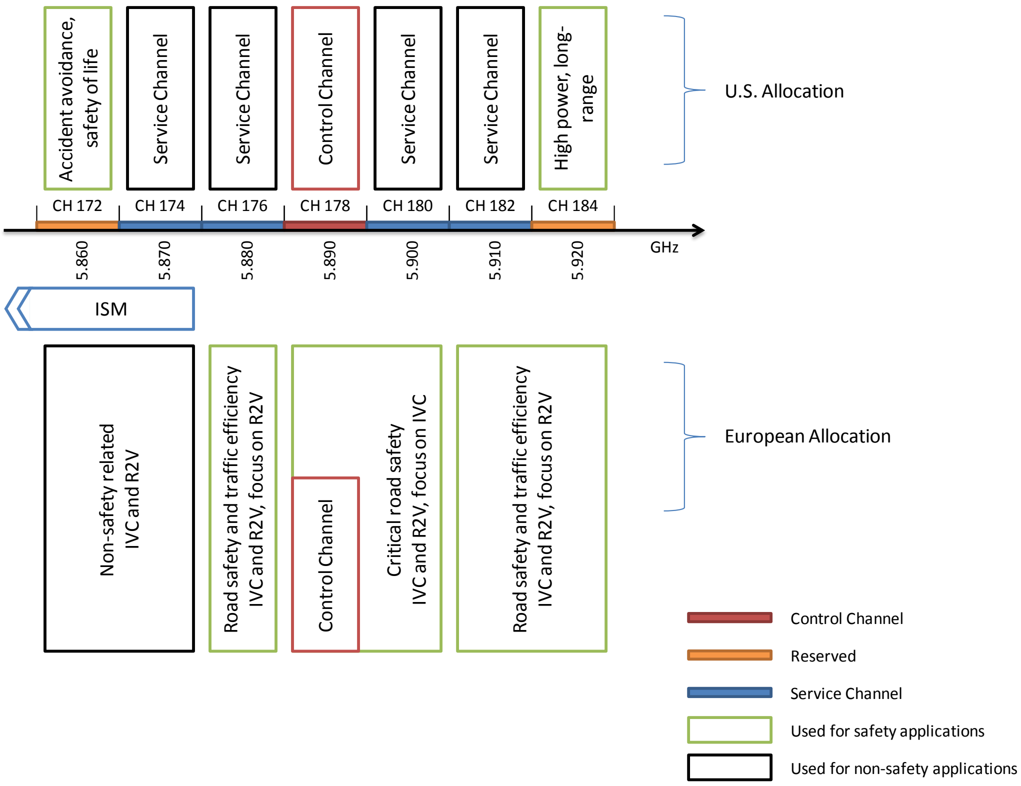


Figure 3.1: DSRC spectrum band and channels in the U.S. and Europe (from [27] and [32]).

The allocated spectrum for the U.S. consists of one Control Chanel (CCH) (CH 178) at the center and six Service Channels (SCHs), three to the left and three to the right. Besides the occasional advertisement of applications in the SCHs, the CCH is exclusively used for the transmission of safety and control messages. The two channels on the edges are reserved for future applications. The left one (CH 172) is reserved for accident avoidance and safety of life applications, while CH 184 is reserved for high power, long-range safety applications. The service channels can be used for both, safety and non-safety applications. The different channels cannot be used simultaneously, but each station continuously switches from the control channel to one of the service channels [34].

In Europe there is already an ISM band allocated in this frequency spectrum. Thus, it is not possible to adopt the U.S. allocation identically. This ISM band overlaps with the two lower channels (CH 172 and CH 174), therefore, a slightly different alignment of the channels was chosen. The safety channel on the left edge and the next service channel are merged to a non-safety related channel with a bandwidth of 20 MHz. The control channel remains at the same position as in the U.S. allocation, but is merged to a 20 MHz channel designed for critical road safety communication. The remaining channels (on the left and right of the critical road safety channel) are used for non-critical road safety and traffic efficiency applications.

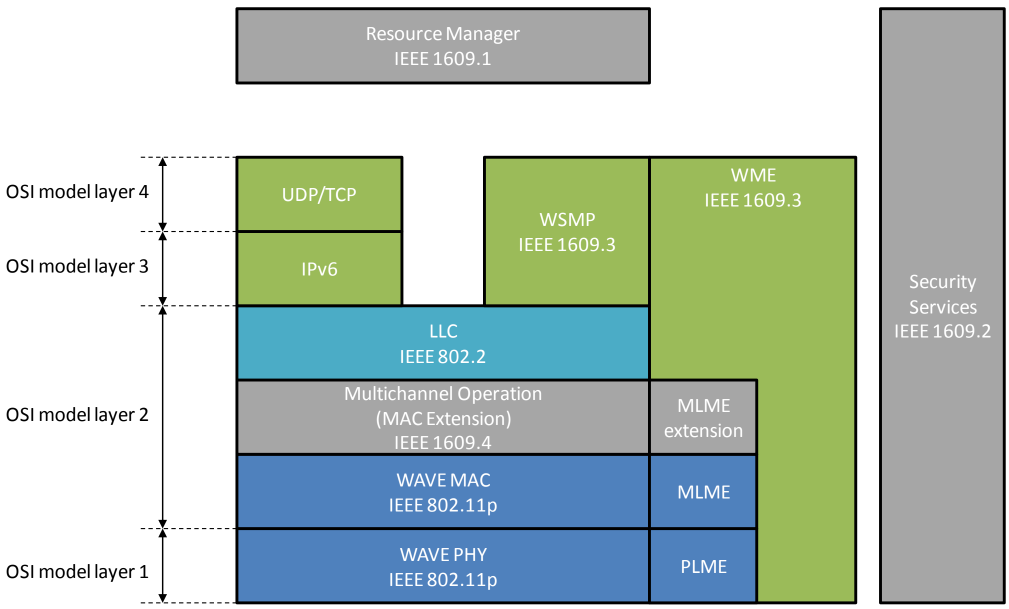


Figure 3.2: The WAVE protocol stack and its relationship to the OSI model and 802.11p [35].

Wireless Access in Vehicular Environment (WAVE) is a set of standards (IEEE 802.11p and IEEE 1609.x) with the purpose to facilitate wireless communication for VANETs [35] and it is the core part of DSRC [28]. The WAVE protocol stack and its relationship to the OSI model and IEEE 802.11p is shown in Figure 3.2 (from [35]). Details on this protocol stack are also described in [36, 37].

As the figure shows, for the physical (PHY) and Media Access Control (MAC) layers 802.11p is used, which is an amendment of the IEEE 802.11 standard for vehicular environments. This includes also the management functions Physical Layer Management Entity (PLME) and MAC Layer Management Entity (MLME) for the corresponding layers. Additionally, WAVE needs to switch between the CCH and the SCH, therefore, a MAC extension for multichannel operations is added, as specified by IEEE 1609.4. On top of these layers, two alternative protocols are supported by WAVE: traditional IPv6 and the proprietary WAVE Short-Message Protocol (WSMP). This way WAVE differentiates between high priority safety messages with low latency requirements and traditional communications based on TCP with relaxed communication requirements. The integration of TCP/IP, the specification of WSMP and the definition of cross layer management function (WAVE Management Entity (WME)) is described in IEEE 1609.3.

### 3.2.2 IEEE 802.11p Basics

As previously mentioned, 802.11p is an amendment of the IEEE 802.11 standard, designed for vehicular networks. Thus, WAVE also uses a Distributed Coordination Function (DCF) as the base access method to share the wireless medium [38]. More precisely, the 802.11p uses a variant of the Enhanced Distributed Coordination Function (EDCF) from the IEEE 802.11e standard [39], which allows contention-based prioritized QoS support[40]. This EDCF is based on a standard Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) (see [38] for details) as MAC protocol [41, 42, 43].

This DCF uses a four-way handshake protocol, known as Request-to-Send/Clear-to-Send (RTS/CTS) and acknowledgement to address the hidden terminal problem and to make the communication reliable [44]. This mechanism is used in point-to-point communication, however, in a multicast communication scenario (i.e. with multiple destinations, which is the case when a message is broadcast to all neighbors in communication range) this would lead to packet storms around the sender [45]. Therefore, broadcast packets are not protected by this mechanism in 802.11-based protocols [46, 47, 48].

This has serious implications on the design of dissemination protocols on top of the WAVE stack. Whereas unicast messages are acknowledged and thus the sender can determine if the transmission was successful or not, multicast packets are not acknowledged, thus it is a best effort service. Therefore, it is a very challenging task to develop such broadcast protocols – especially over multiple hops – for VANETs. The severity of this problem is amplified by the fact that an overwhelming majority of the envisioned applications use a multicast addressing scheme.

### 3.2.3 IEEE 802.11p Transmission Characteristics

The previously discussed DSRC communications stack enables a wireless transmission range up to 1000 meters [23, 49, 50, 51]. Such a transmission range of broadcast safety messages is sufficient for the bulk of short-range applications discussed in Chapter 2. But it is important to note, that this transmission range is an upper limit and the effective range is influenced by many circumstances such as data rate, power, bandwidth, and topography[13]. The influence of environmental factors like topology and vegetation is significant. According to Böhm et al. the transmission range can drop under 100 m, therefore, amplifying the tight timing requirements of active safety applications [52, 53].

For example, Schmidt et al. evaluated in [54] the causes for degredation of the transmission range by extensive simulations. They identified interference of other vehicles as the main cause for packet losses. Their results show that the reliable transmission range can drop down to 100 m, i.e. it is reduced by up to 90%. These results were confirmed by the authors in [55] by a real-world experiment. In those experiments, shadowing was identified as another cause for packet losses.

Such a negative impact of acNLOS conditions onto the reception rate of transmitted packets are also experienced by other authors. In [56] the authors evaluated the data of an extensive field trial, and state that Non-Line-of-Sight (NLOS) conditions require a careful attention at the physical layer, in order for being able to provide a transmission range useful for safety applications.

In [57], Gozálvez et al. conducted a wide range of measurements to analyze different environmental settings and their impact onto the communication performance. The authors also state that NLOS conditions provoked by large vehicles make the maintenance of stable links difficult. Moreover, the authors point out that NLOS conditions caused by sharp curves or the presence of buildings drastically reduce the transmission range and the link quality. In such situations, the connectivity gets already lost after a few meters a vehicle moves into such a condition.

Paier et al. observed in [58, 59] a significant decrease of the transmission range by increasing the data rates (the reliable transmission range dropped from 700 m at 3 Mbit/s to 100 m at 27 Mbit/s). They experienced also a significant impact of environmental effects and shadowing onto the transmission performance.

Martelli et al. also conducted an extensive field test to measure the performance of 802.11p and published the results in [60]. According to that study, the Packet Delivery Rate (PDR) already drops significantly within short distances. Already at a transmission distance of around 70 m, the PDR is only about 30%, at 110 m only about 10%. Furthermore, they show that NLOS conditions impair the benefit achievable through safety applications. As one possible countermeasure the authors underline the use of multi-hop information dissemination, at least if a high percentage of vehicles is equipped with DSRC devices.

Furthermore, Han et al. conclude in their analytical study ([40]), that although 802.11p provides an effective service differentiation mechanism, it demonstrates a poor performance in dense networks. Thus, the reliability of packet transmissions is low in such environments. Further extensive channel measurements and observed characteristics and their impact onto the performance and the design of safety systems is presented in [61]. Additional analysis of the DSRC communication characteristics and its reliability for the use for safety application can be found in [62] and [63].

### 3.2.4 Summary of Radio Hardware Communication Characteristics

In the following we summarize the discussed transmission characteristics of 802.11p and briefly outline their implications onto the dissemination protocols used on top.

#### Communication Types

Based on the DSRC communication stack, applications can use either unicast or multicast routing [43]. These addressing types are implied by the use of the 802.11 MAC which provides two possible transmission types:

- *Link layer unicast:* A message is addressed exactly to one target node in the vicinity of the sender. Thus, this is a point-to-point communication, using the DCF as explained previously.

- *Link layer broadcast:* A message is addressed to all neighbors in communication range. This is a point-to-multipoint communication scheme, which transmits a message in a best effort manner.

Routing protocols built on top of 802.11 can choose from these two addressing types. In VANETs typically a position-based routing protocol is used for multi-hop unicast, where the forwarding decision is based on the positions of vehicles [64, 65]. For the hop-by-hop transmission the link layer unicast is used.

The link layer broadcast is used by cooperative VANET applications to periodically exchange vehicle data, such as position, velocity, etc. This addressing scheme is also used to flood a warning messages into a specific geographic region[66]. Moreover, it is also used by many unicast routing protocols for route discovery[67].

### Transmission Range and Communication Reliability

As we have seen, DSRC enables a transmission range up to 1000 meters. Such a transmission range would be sufficient for the majority of applications discussed in Chapter 2. However, this transmission range is achieved only in a best case scenario under perfect environmental conditions. Under real conditions – as proven by various real-world experiments – the transmission range degrades drastically. There are two main causes for this degradation: NLOS conditions and interference.

- *NLOS:* If two communicating participants are not in line of sight – i.e. they are separated by other vehicles, buildings, or other obstacles – the transmission can either become unstable or even the connection can be lost. Thus, the effective transmission range can be very short, compared to the range under ideal conditions.
- *Interference:* With increasing distance between two communicating participants the probability of packet losses increases due to interference. The degree of interference is proportional with the vehicle density and the amount of data transferred. Thus, these two factors also negatively influence the transmission range.

These factors lead to a serious degradation of the transmission range, which could result in insufficient performance of the communication system for safety applications with tight latency requirements. As shown in [60], already at a distance of 70 m only about 30% of the sent broadcast packets were received. Thus, these real-world experiments lead to the conclusion, that effective transmission range is much shorter as commonly assumed. Therefore, also many short-range applications would benefit from a multi-hop information dissemination. Especially in the presence of NLOS conditions, there is a need of multi-hop communication, otherwise the benefit of safety applications is minimized in such situations compared to traditional, sensor-based safety systems.

### Communication Latency

As introduced in Section 2.3, allowable latency is another important application requirement used as a criteria for the classification of VANET applications in Section 2.4. Therefore, it is important to clarify the implications of 802.11p for safety applications regarding this quality criteria.

First, it is obvious that the dissemination delay requirement is inverse proportional to the dissemination range. I.e., by increasing the dissemination range, the delay requirements of safety applications get more relaxed due to the gained time a driver has to react in advance. Therefore, the delay is relevant especially for short-range safety applications. Regarding the reduced effective transmission range due to environmental conditions or high data transmission rates, the dissemination delay should also be considered for mid-range applications.

As Eichler et al. analyzed in [34], in a scenario with approximately 5.9 neighbors within transmission range, the end-to-end delay of high priority messages goes up to 1 sec, compared to the 100 msec latency requirement of most safety of life applications [68]. Similar results were reported in [68], where the delay provoked by contention was analyzed by varying the transmission range. Thus, in such scenarios the tight delay requirements of safety application cannot be met anymore.

Therefore, the dissemination of information in dense networks is very challenging regarding the delay requirements. By extending the dissemination range through multi-hop forwarding of warning messages, also the delay problem could be thwarted. This is especially true for event-triggered dissemination of warning messages, because such applications could benefit from the increase of the dissemination range.

## 3.3 Overview of Vehicular Communications

Vehicular Communications (VC) identifies the exchange of information over a wireless medium between nodes which participate directly or indirectly in the traffic. Directly participating nodes are regular vehicles – equipped with an On Board Unit (OBU) for communication – which change their positions over time, whereas indirectly participating nodes are Road Side Units (RSUs) which only exchange information with vehicles, thus they can only indirectly affect the traffic. For the communication over the wireless medium the IEEE 802.11p standard [69] is envisioned.

Furthermore, there are two kinds of communication types: one-way and two-way communication. In one-way communication a link layer broadcast is sent to vehicles in communication range. This is a fire and forget message, i.e. there are no acknowledgements provided by the MAC layer. In two-way communicating a dialogue is established between the source and destination node.

According to Sichitiu and Kihl [70], VC can be divided into three major communication system types:

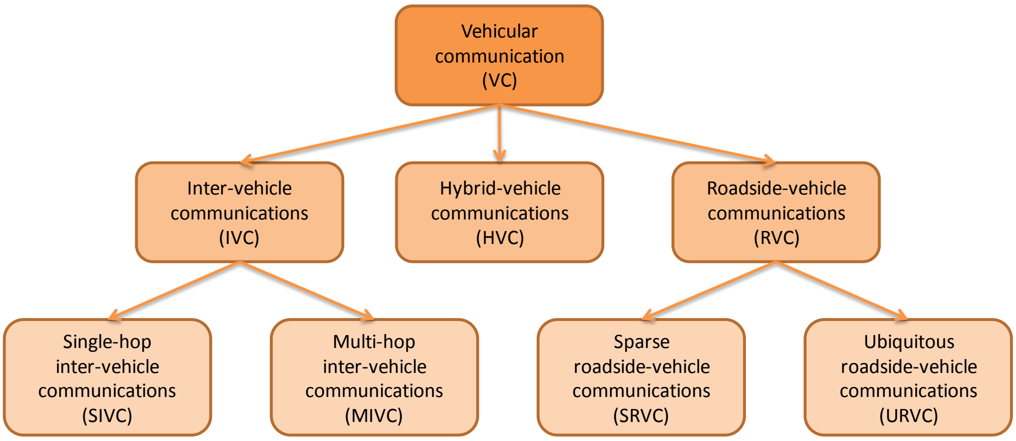


Figure 3.3: Classification of vehicular communication [70].

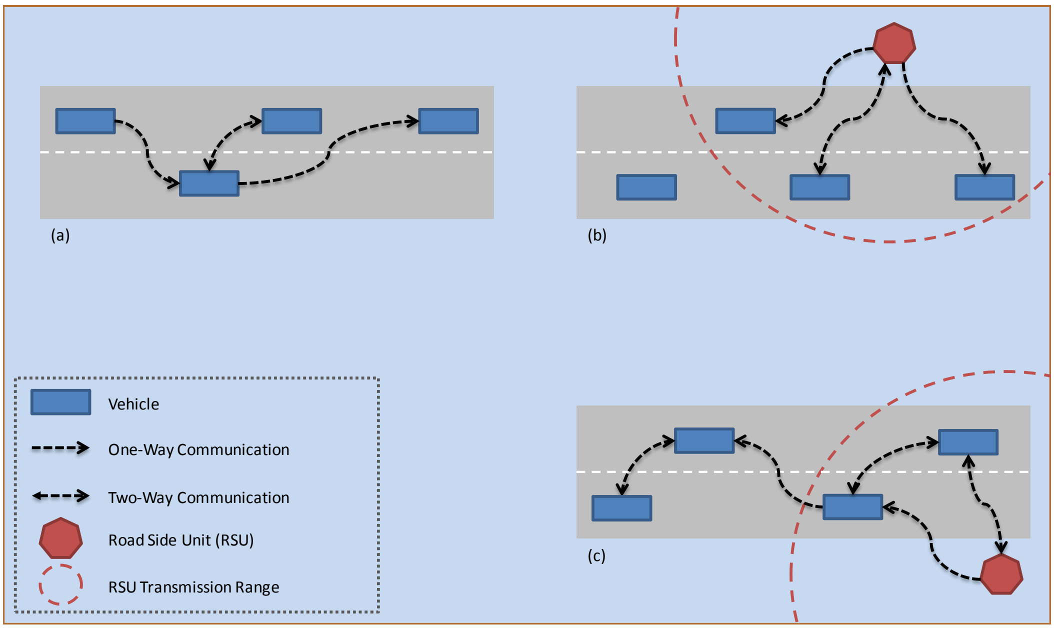


Figure 3.4: a) Inter-Vehicle Communications (IVC), b) Roadside-Vehicle Communications (RVC), c) Hybrid-Vehicle Communications (HVC).

1. Inter-Vehicle Communications (IVC),
2. Roadside-Vehicle Communications (RVC), and
3. Hybrid-Vehicle Communications (HVC).

This distinction is based on the node types of the communication partners: Communication taking place exclusively between vehicles is called IVC, whereas vehicle communication only with infrastructure is named RVC. HVC is the combination of the other two types, i.e. a vehicle can communicate to another vehicle as well as to a RSU. Note that IVC, RVC, and HVC are synonyms to the terminology used in the previous chapter, respectively, to V2V, V2I/I2V, and V2X communications. Figure 3.3 (taken from [70]) depicts this classification which is detailed in the following.

### 3.3.1 Inter-Vehicle Communications

Inter-vehicle communications – also known as V2V and Car-to-Car (C2C) communications – is illustrated in Figure 3.4 a). As we can see, only vehicles equipped with an OBU communicate with each other. Such vehicles communicate exclusively with each other, there is no communication with RSUs at all. The information which is communicated from one vehicle to another is based on data gathered from own physical sensors and on information received – and possibly aggregated with sensor data – from other vehicles.

IVC can be further divided into Single-hop and Multi-hop Inter-Vehicle communications:

- *Single-hop Inter-Vehicle Communications (SIVC):* A message is only transmitted to one or more direct neighbors within transmission range. Thus, no routing takes places to relay the message to nodes not directly connected to the originator.
- *Multi-hop Inter-Vehicle Communications (MIVC):* A message is routed via multiple hops to a distant destination node.

SIVC is used for applications which rely only on information gathered from neighboring cars in a communication range of a few hundred meters (typically, the transmission range is assumed to be around 300 m [62, 71]). This kind of applications uses mostly a periodic exchange of car specific data like position, velocity and heading. This information can be used to warn the driver about dangerous situations in the surrounding of the vehicle. An example is the Cooperative Collision Warning (CCW) application as described in [71, 72, 2, 73].

MIVC is used for applications which require data dissemination beyond the direct communication range. A message is forwarded by multiple hops, thus the information can also reach distant vehicles. Typical use-cases for MIVC are traffic monitoring applications which gather traffic related information of roads and aggregates them in a way that the driver can benefit from the extracted information. Examples are traffic monitoring systems which accumulate information of large road segments to provide an up-to-date traffic-flow information of these segments to the driver (see amongst others [74, 75, 76, 77]).

### 3.3.2 Roadside-Vehicle Communications

In RVC – also known as V2I and Car-to-Infrastructure (C2I) communications – a message is always exchanged between a RSU and an OBU, as illustrated in Figure 3.4 b). Therefore, an application based on RVC prerequisites a RSU in communication range to be functional.

Many important applications like Traffic Signal Violation Warning and Stop Sign Violation Warning are based on information received from RSUs [2]. Moreover, RSUs can provide also system-level services, e.g. for VC security and privacy [78, 79, 80, 81], access point to the internet [82, 83, 84], collection of aggregated traffic information [85, 78, 86], and assistance of information dissemination [87].

According to [70], RVC can occur in two manifestations:

- *Sparse Roadside-Vehicle Communications (SRVC):* RSUs are deployed only sparsely at important hot-spots. The importance of such a hot-spot depends on the applications: E.g. a busy intersection for a Traffic Signal Violation Warning application [2], or dangerous curves on a highly frequented road for a Curve Speed Warning application [2] could be such important hot-spots. Also non-safety applications are conceivable to make use of such hot-spots, e.g. a roadside service finder for gas stations, restaurants, etc. [7, 12] to advertise their prices or a parking garage disseminating information about free parking slots [88, 89, 90].

- *Ubiquitous Roadside-Vehicle Communications (URVC):* RSUs are deployed at every hot-spot, thus the whole road network is covered by them. This is of course a vision, because such an extremely high deployment density of RSUs would require considerable investments, and is therefore impractical especially at the early rollout stages of VANETs [91].

### 3.3.3 Hybrid-Vehicle Communications

Both communication systems, IVC and RVC, have their eligibility, advantages, and disadvantages. Their pros and cons can be summarized as follows.

The main advantage of IVC is that it is not necessary to deploy costly infrastructure. Moreover, by using multi-hop message forwarding the communication range can be extended as needed by applications. Also there is a significant amount of applications which can only be realized by using IVC [2, 74, 75, 76, 77]. On the other hand, the utilization of vehicle communications based solely on VANET-enabled vehicles has the disadvantage that – especially in the early rollout – applications may suffer from network partitioning (cf. [92]). I.e., having a low market penetration of VANET-capable vehicles, there is a high probability that a message cannot progress further in the dissemination progress because there are no other vehicles in communication range capable to further relay the message. Thus, either the message gets lost or it has to be transported physically by the vehicle, resulting in a significant increase of the communication delay [93]. Another important disadvantage is that there is a significant number of applications which require dedicated infrastructure communication.

The advantage of RVC – besides of applications solely using it – is that there are many applications which use only infrastructure to vehicle communications, thus these applications are independent of the OBU equipment ratio of vehicles. I.e., this applications can be also successfully deployed in the early deployment stages. Furthermore, RSUs can have special hardware, e.g. a radio unit with high transmission power, thus, applications can benefit from such infrastructure [94]. On the other hand, as we have already mentioned, the deployment costs proportionally increase with the deployment density of RSUs. Because this is a serious problem, a number of researches focus on the optimization of RSU placement [92, 91, 95, 96, 97, 98].

Because the disadvantages of both communication systems are very significant, it thus stands to reason that both types should be applied simultaneously, i.e., vehicles can communicate both with other vehicles and RSUs. This type of communication system we call HVC, also known as Car-to-X (C2X). This way, there is an interplay of both systems, combining their advantages and eliminating the disadvantages.

Thus, RSUs can be used e.g. to overcome the network partitioning problems if the penetration rate of deployed OBUs is low [92, 99, 94]. This can be used to successfully deploy VANET applications even in the early rollout phase. Furthermore, by using IVC, the scope of RVC-based applications can be extended significantly, i.e. allowing those applications to be fully functional even in areas with sparsely deployed RSUs.

For these reasons, in VANETs both communication systems should be considered and used. RSUs are a special case of nodes with OBUs: their velocity is zero, thus they are static, but otherwise they are identical with vehicular nodes (besides the special hardware applied). Therefore, in this work, we do not explicitly distinguish these two types, but use them as a synonym. If not stated otherwise, we assume a VANET with C2X communications, thus we are evaluating HVC systems in general.

## 3.4 Mapping of Application Requirements to Routing Attributes

As we have seen, VANET applications have specific requirements onto the communication protocol. In this section we close the gap between those application requirements and the communication mechanisms provided by IEEE 802.11p, i.e. we evaluate which networks protocols can be used on top of IEEE 802.11p in order to fulfill the requirements. This way we deduce a set of communication patterns which can be used to realize the discussed applications.

### 3.4.1 Communication Participants

The first application requirement we discussed in Section 2.3 was the differentiation of communication participants needed by the applications. It is obvious, that from an application perspective it makes a difference if RSUs are used or not. For example, an Internet Service Provisioning (ISP) application could presuppose RSUs which act as gateway for the access onto internet services. On the other hand, there is no need to differentiate this attribute from a network perspective because it is assumed that RSUs are using similar radio hardware to OBUs of vehicles. For the network protocol it does not matter if a node is a RSU or an OBU. Therefore, in this work, we do not differentiate between IVC and RVC, we assume a hybrid network.

### 3.4.2 Dissemination Range

This application level attribute has a significant influence onto the choice of the network protocol: applications which are using a short communication range (i.e. in the range of a few hundred meters) can rely on one-hop communication whereas for applications requiring a larger communication range (classified as medium and long-range communication), a multi-hop dissemination protocol is needed. Therefore, in VANETs the following two dissemination classes are distinguished as a basic routing attribute:

- *one-hop*, and
- *multi-hop* dissemination.

As discussed in Section 3.2.4, the transmission range of IEEE 802.11p can drastically degrade in NLOS situations or dense networks with a high traffic volume. Therefore, also for applications which require only a short-range transmission, a multi-hop dissemination should be considered. Especially event-triggered applications would benefit of such an enhanced range, because the occurrence of such an event represents typically an unpredicted condition, thus the missing of such warning packets can have severe consequences onto the road safety.

### 3.4.3 Allowable Latency

The latency is another important criteria for the selection of an appropriate dissemination protocol. As we have seen, IEEE 802.11p facilitates the transmission of safety and non-safety messages with a low delay under normal network conditions. On the other hand, with increasing node density also the latency increases due to congestion. Thus, in dense networks with high message transmission rates it is a challenging task to transmit messages with a low latency.

Regarding the VANET applications from Chapter 2, four application classes have a low latency requirement (as illustrated in Figure 2.2 on page 17): the three *Active Safety* application classes *Collision Avoidance*, *Crash Imminent*, *Abnormal Traffic and Road Conditions*, and the *Improved Driving* application class *Assistance and Cooperative* movement. These applications use the periodic exchange of information – also called *beaconing* – or an event-triggered transmission of messages upon the occurrence of an unexpected situation.

Mid and high latency applications also rely on periodic or event-/user-initiated transmission of information. The latency requirement affects these two transmission modes from a networking perspective. From the allowable end-to-end transmission delay the allowable delay of per-hop (re)transmissions and the periodic delay time (i.e. the beaconing interval) can be derived.

The delay time ($Dt$) of a node for retransmitting a message includes the time to process a received message ($Pt$), to execute the routing protocol ($Rt$), the access time of the wireless medium for retransmitting the message ($At$), and finally the transmission time of the message ($Tt$). Thus, the end-to-end delay is the sum of the delay time for transmission of every hop and increases proportionally with the number of hops. Having $n$-hops, the end-to-end delay ($Dt_n$) can be expressed as follows:

$$Dt_n = \sum_{i=1}^{n} Pt_i + Rt_i + At_i + Tt_i$$

Applications which use a periodical message dissemination introduce an additional delay, the so called beaconing interval ($Bt$). The beaconing interval specifies at which rate information is exchanged periodically. For example, according to [2] the allowable latency for the Intersection Collision Warning (ICW) application is around 100 $msec$. Thus this implies, that information such as traffic signal status, timing, directionality, position of the traffic signal stopping location, etc., needs to be transmitted with a frequency of at least 10 $Hz$ (assuming one-hop communication). When multi-hop beaconing is used, then the maximum end-to-end transmission delay $BDt_n$ is in the worst case the sum of the beaconing interval plus the retransmission delay per transmitting node:

$$D_b t_n = D t_n + n \cdot Bt$$

Because the IEEE 802.11p link layer broadcast is not reliable (explicit acknowledgements are not available), the use of implicit acknowledgements based on overhearing retransmissions of a messages can be used to enhance the reliability of multi-hop information dissemination [100, 101, 102, 103, 104, 105]. Upon a broadcast a node starts a timer and overhears the wireless channel for retransmissions of that message from nodes in its vicinity. If no such retransmissions are detected, the node can perform a rebroadcast after the timeout. For the determination of an appropriate timeout value the allowable latency and the estimated number of retransmissions can be used. The allowable per-hop delay limits this timeout used by the routing protocol.

The retransmission delay depends on the hardware and MAC protocol used, therefore it cannot be directly influenced by the routing protocol. Thus, the following routing attributes are of importance for an information dissemination protocol in VANETs, which can be derived from the latency application requirement:

- *beaconing interval*, and
- *retransmission timeout*.

### 3.4.4 Directionality

Basically, DSRC provides two communication modes: broadcast one-way and unicast two-way communication. One-way communication means that the DSRC unit broadcasts a message to all nodes in communication range, whereas in two-way communication a dialogue is established between two DSRC modules [2]. Thus, these two communication modes satisfy the directionality application requirement.

Unfortunately, this is only true for one-hop communication, because these two DSRC communication modes are designed only for direct communication with nodes in the vicinity. For multi-hop one-way communication this makes no difference, i.e. the DSRC broadcast mode can be used without any limitation for this case. But for a multi-hop two-way communication the routing protocol has to establish the dialogue itself between two distant communicating parties, based on the two basic DSRC operation modes. Because the DSRC unicast mode already implements the acknowledgements of transmissions and due to the use of the EDCF (c.f. Section 3.2.2), it is self-evident to use it for multi-hop two-way communication.

These two multi-hop dissemination protocols are designed for different application situations and their directionality mode perfectly fits the requirements of application classes using such a dissemination protocol. Multi-hop broadcast is typically used by safety applications which warn vehicles e.g. about abnormal traffic conditions. In this case, the originator of a message has no knowledge about the exact destination, it specifies only a destination region. All vehicles within that region are potential receivers of the warning message. On the other hand, applications such as Instant Messaging (IM) need a connection between two well known communication parties. Thus, over an established connection several messages are exchanged, enabling a dialogue between the communication parties.

Therefore, we can conclude that one-way communications implies a multicast addressing (in the case of VANETs realized as a Geographic Broadcast (GeoCast)) whereas two-way communications presupposes a unicast addressing scheme.

### 3.4.5 Addressing

Both, single-hop unicast and single-hop multicast do not require routing, a message is directly transmitted to the destination using a IEEE 802.11p enabled communication device. On the other hand, multi-hop transmission requires a routing protocol specialized on VANETs. For multi-hop unicast communication a position-based routing protocol represents the most promising approach in VANETs [106, 107, 108, 109, 64, 110, 65, 111]. This implies the presence of a location service, because the source node has to determine the position of the destination node.

For multi-hop multicast communication in VANETs generally a target geographic region is addressed, in which a message is flooded to all vehicles. For this kind of VANET communication the so called GeoCast dissemination protocol is used [112, 113, 114, 115, 116]. Depending on the position of the source node and the destination area, two types of GeoCast protocols can be distinguished:

- *Local GeoCast:* The originator of a message resides inside the destination region, i.e. the message can be directly flooded into this region.

- *Remote GeoCast:* The originator addressed a distant region, thus the message needs to be transported first to that region. This can be done e.g. by using a position-based anycast communication.

This way, the VANET applications from Chapter 2 can be realized by using a geographic addressing scheme. Both, unicast and multicast multi-hop dissemination protocols retransmission decisions are based on such addresses.

### 3.4.6 Transmission Trigger

A periodically triggered transmission can be typically implemented as a link layer broadcast. This way, information can also be transported over multiple hops, either as atomic or aggregated values. This deferred forwarding can be used in cases of no tight latency requirements of the application.

The periodic multi-hop dissemination of information is expensive in terms of required bandwidth, especially if the dissemination distance is large and the information generation frequency (beaconing interval) is high. Therefore, either the dissemination hop-count is very low or the received and sensed information are aggregated to minimize the amount of transmitted data. For this reason, routing protocols which use neighborhood information (e.g. the Optimized Position-based Gossiping (OPbG) [117] and Advanced Adaptive Gossiping (AAG) [118] protocols) limit the range of beaconing to gather such information to one- or two-hops. On the other hand, for applications which require the accumulation of information over large road segments the gathered data is highly aggregated to prevent the saturation of the wireless link.

Event-triggered messages involve typically the notification of vehicles about abnormal road and traffic conditions in a specific region. Therefore, a messages has to be flooded immediately to all nodes in that region. It should be noted, that it could be desirable to hold such an information over a specific time period in a region. Therefore, periodic rebroadcast of that information can be applied.

There are also unicast-based event-triggered applications, like E-Payment (EPay) and Area Access Control (AAC). User-initiated communication is a subclass of event-based applications and are also typically based on two-way unicast communications.

To summarize the implication of the transmission trigger onto the routing protocol we can state, that applications which require periodic information dissemination are based on beaconing whereas event-driven and user-initiated applications make use either of unicast or multicast communication, both using geographic addresses.

### 3.4.7 Information Accuracy

As already mentioned, the dissemination of information over multiple hops is expensive – in terms of required bandwidth. The number of vehicles is proportional to the square of the dissemination range. It means, if a message is disseminated twice as far, then four times as many vehicles are reached which potentially rebroadcast that message. This can lead to the so called *broadcast storm problem* [119, 120]. What's even worse, if those nodes all insert their own atomic information into that message, then it is clear that the message size grows out of scale. Thus, this will not scale if atomic (accurate) information are disseminated over a large distance.

Therefore, several aggregation schemes were proposed to overcome this scalability problem [74, 78, 121, 92, 77]. These approaches minimize the required bandwidth by averaging and summarizing information based on criteria like similarity, distance, etc. Thus, the accuracy of information gets lost but on the other hand the amount of data transmitted is minimized.

As a rule of thumb it can be summarized that atomic information should be exchanged periodically only over short distances. The event-based transmission of messages should not exceed mid-range distances. Over large distances only highly aggregated data should be exchange to minimize the amount of transmitted data. Thus, the level of aggregation of data needed by applications influences the achievable communication range.

### 3.4.8 Summary

As we have discussed, applications impose several requirements onto the communication system which should be considered by routing protocols designed for VANETs. Table 3.1 gives an overview of the mapping of application requirements to such routing attributes.

| **Application Requirement** | **Routing Properties** | **Description** |
|---|---|---|
| *Communication Participants* | - | From a network perspective, there is no difference between a RSU and an OBU. Therefore, there is no network level attribute based on this differentiation which should be considered by routing protocols. |
| *Dissemination Range* | Single-Hop and Multi-Hop Routing | The dissemination range required by a VANET application prescribes if a multi-hop routing protocol is needed or not. Most of the applications with a low dissemination range requirement can be realized by a single-hop communication protocol whereas higher dissemination ranges require a hop-by-hop retransmission of a message. |

| | | |
|---|---|---|
| *Allowable Latency* | Beaconing Interval and Retransmission Timeout | From the allowable latency requirement two important routing properties can be derived: First, for periodic dissemination the beaconing interval and for immediate dissemination the retransmission timeout. The retransmission timeout can be used to allow a deferred transmission of a message, and more importantly, to enhance reliability by introducing a retransmission of a message as previously described. |
| *Addressing* | GeoCast or position-based Unicast Routing | Unicast addressing implies a position-based, greedy forwarding protocol whereas multicast is typically based in VANETs on geographical group membership and is mostly realized as a GeoCast. |
| *Directionality* | Link layer Unicast/Broadcast | One-way communication is simply realized by a link layer broadcast, because there is no need for a dialogue between two communication parties. On the other hand, for a two-way communication link layer unicast can be used. |
| *Transmission Trigger* | Beaconing or Instant Dissemination | Periodic message dissemination implies the use of a beaconing mechanism in VANETs, whereas the dissemination of a message based on an event or initiated by a user should be disseminated instantly, or at least with a delay which does not violate the applications latency requirement. |

| | | |
|---|---|---|
| *Information Accuracy* | Aggregated or Atomic Information Dissemination | If an application requires atomic information, then the routing protocol has to retransmit a message without modifying the information, i.e. the retransmitted information is exactly the same as on reception. On the other hand, if an application does not need atomic information, then aggregation techniques can be used to decrease the amount of data needed to be transmited over the wireless medium. |

Table 3.1: Mapping of application requirements onto routing properties.

## 3.5 Classification of Communication Mechanisms

As we have seen in the previous sections, VANET applications require different communication types. Such applications need single-hop as well as multi-hop communication, periodic broadcast or instant message dissemination, routing based on geographical addresses, and the dissemination of both atomic and aggregated information. Therefore, in this section we group such typical communication requirements to dissemination protocol classes. The idea is to have few such protocol classes which are the building blocks for most VANET applications.

The result of this deduction of application requirements to IEEE 802.11p MAC layer communication primitives and the grouping of those to VANET communication classes is similar to the work of Schoch et al. in [4]. In a different way of that study, the deduction of these communication patterns was introduced in this work, as described in the previous sections. Additionally, the resulting communication patterns are strictly examined from a network perspective view, this means, not considering application level properties or composed dissemination schemes, which are built of basic communication patterns. Such advanced communication schemes are discussed in the subsequent Section 3.6. Also information aggregation is not regarded in this section, which in fact is orthogonal to the used dissemination protocol and can be implemented on top of different dissemination schemes.

In the next subsections we describe the basic communication patterns built on top of IEEE 802.11p, which can be used to realize the applications presented in Chapter 2. Based on these basic communication types, we describe more advanced communication patterns in the subsequent section.

### 3.5.1 Unicast

Besides the link layer broadcast, the single-hop unicast is one of the basic communication technique provided by IEEE 802.11p. Through unicast communication a dialogue is established to an adjacent vehicle in communication range. Thus, sent messages are acknowledged by the receiver. Because applications which need unicast communication mostly require a bidirectional communication between source and destination (cf. Chapter 2), the IEEE 802.11p unicast communication perfectly fits for such applications using single-hop communication. In the case of multi-hop communication, the network layer protocol has to ensure the establishment of such a dialogue. Figure 3.5 shows this communication pattern and is described in the following.

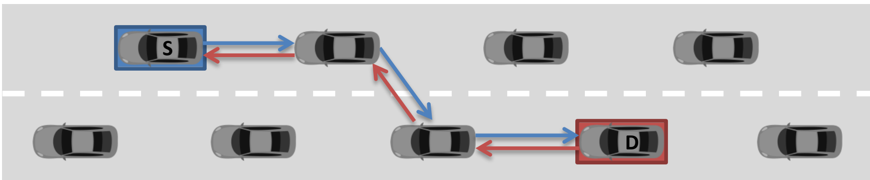


Figure 3.5: Example for unicast communication (adapted from [1]). The vehicle marked in blue on the left initiates a unicast message. This message is forwarded hop-by-hop to the destination vehicle, marked in red. The destination vehicle sends a response message which is routed back to the source, possibly on a different route. Thus, this communication is bidirectional and is hold over time.

#### Description

Point-to-point bidirectional communication from a source node to a destination and back. A message is routed hop-by-hop to the destination node. Aside from routing, the communication only takes place between the source and destination node. A typical use-case is when two nodes exchange private information, e.g. in the Emergency Vehicle Signal Preemption (EVSP) application the emergency vehicle only aims to communicate with the RSU located at the traffic light.

#### Communication Mechanism

As already mentioned, it is obvious to use IEEE 802.11p unicast to realize a multi-hop bidirectional communication between two parties. The routing of a message over multiple hops can be achieved by using different routing approaches. Examples are topology routing protocols which are mostly adopted from Mobile Ad-hoc Networks (MANETs) like Optimized Link State Routing (OLSR) [122], Dynamic Source Routing (DSR) [123] and Ad-hoc On-Demand Distance Vector Routing (AODV) [124]. Another class is the position-based routing protocols like Geographic Source Routing (GSR) [125], Anchor-based Street and Traffic Aware Routing (A-STAR) [126], and Greedy Perimeter Stateless Routing (GPSR) [127]. There do exist also other approaches like cluster-based and broadcast routing, see [64] for more details. However, the most promising approach represents the use of a position-based routing protocol [64, 109, 111, 65]. Such protocols significantly outperform topology-based approaches as shown in several evaluations [128, 129, 65].

Note that subsequent messages from a source to a destination not necessarily take the same route, because typically each forwarding node's routing decision is based on the actual local network topology. This holds also for the response message which is routed back to the source node. This way, a stable connection can be hold over time even in networks with such dynamic characteristics like VANETs.

#### Addressing

Unicast represents a strictly point-to-point communication. When using a position-based routing protocol, the location of the destination node has to be known. Therefore, the existence of a location service is a precondition for the use of this communication mechanism.

#### Trigger

Unicast communication is either event-triggered or user-initiated. All applications reviewed in Chapter 2 using unicast communication are triggered this way.

#### Directionality

Usually, it is a bidirectional communication between the two communication participants, i.e., these participants exchange several messages over the same connection. Thus, this connection has to be hold over time. One-way communication would be a special case, i.e. the destination node would not answer upon reception of a message.

#### Dissemination Range

Unicast communication is typically used for short- and mid-range applications. Long-range unicast communication represents a very challenging task because in a highly dynamic network topology like in VANETs stable routes can hardly be maintained. Moreover, in such dynamic environments, the maintenance of up-to-date position information through a location service – which is a prerequisite for multi-hop unicast routing – results in an unjustifiable high overhead. Therefore, for such a use-case other communication infrastructures as VANETs should be considered [130].

#### Applications

According to the classification of VANET applications, the following application classes are using unicast communication:

- Verification of Traffic Participants,
- Vehicle Maintenance,
- Mobile Services, and
- Enterprise Solutions.

As a summary it can be stated, that several applications can be realized by using the unicast communication mechanism, but – especially for longer distances – the establishing of such a communication channel is challenging. Therefore, other communication channels should be considered for these cases.

### 3.5.2 Anycast

Anycast is similar to the previously described unicast communication pattern, both make use of IEEE 802.11p unicast communication. The differences are the addressing scheme and the directionality as depicted in Figure 3.6 and shown in the following description of this VANET communication mechanism.

#### Description

The purpose of anycast is to route a message from a sender to exactly one member of a multicast group. This destination node is not defined by the sender, but selected during the routing process by a given criteria, e.g. the topological distance. The main use-case of the anycast protocol is as a transport mechanism for the remote GeoCast protocol (as

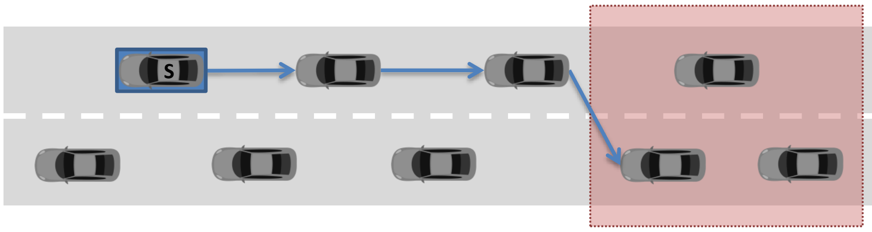


Figure 3.6: Example for anycast communication. The vehicle marked in blue initiates an anycast message by specifying a target region. The target region is marked as a red square. This message is routed hop-by-hop towards that geographical region. Reaching that region, the message is delivered to one vehicle residing in that region.

described in the Section 3.5.4). It means, anycast can be used to transport a GeoCast message – originated outside the target region – towards the target region, also called Zone of Interest (ZoI).

#### Communication Mechanism

Anycast makes also use of 802.11p unicast communication and the multi-hop routing can be realized in a similar manner as the unicast communication pattern. It means, a message is routed hop-by-hop towards the destination region by using a position-based routing protocol. When the message reaches the destination region, the geographically nearest node can be selected as destination. In contrast to unicast, there is no need for a location service, because a vehicle addresses a ZoI geographically based e.g. on digital map data. The routing decisions can be met based on that destination region and on positions of adjacent vehicles (assuming greedy position-based routing is used as transport protocol and vehicle positions are available from a Global Positioning System (GPS) receiver). Therefore, no location service is required for anycast routing, thus it is much more scalable than the unicast approach.

#### Addressing

In the context of VANETs, the multicast group is defined by a geographical region. Therefore, an initiator of an anycast message defines a target region as an address. All vehicles residing in this region are members of the multicast group and are potential addressees of that anycast message.

#### Trigger

An anycast message is typically triggered by an event, be it user-initiated or upon a system event.

#### Directionality

In contrast to the unicast communication pattern, anycast is usually unidirectional. The goal is to transport a message to any vehicle inside the destination region and not to establish a communication dialogue with that car.

#### Dissemination Range

Anycast communication can be used for mid and long-range message dissemination. Because the routing to the destination region is cheap – by means of communication overhead – the distance to the ZoI can be large. This is useful to flood a message into a distant destination region and saves much bandwidth compared with a complete flooding of the region from the source vehicle to the destination.

#### Applications

Use-cases for anycast are applications which require information from a distant region. For example, in the Traffic Information Query (TIQ) application a vehicle could query actual but nevertheless exact traffic information from a road segment several kilometers ahead. Typically, anycast is combined with GeoCast to transport a message to the ZoI where it then can be flooded. An example application is the notification of a distant highway road segment located before an exit about a traffic jam or an accident. This way, drivers have the opportunity to take that exit before they reach the traffic jam.

### 3.5.3 Beaconing

Beaconing is a basic communication service which make use of IEEE 802.11p broadcast communication. Figure 3.7 shows this communication pattern and is described in the following.

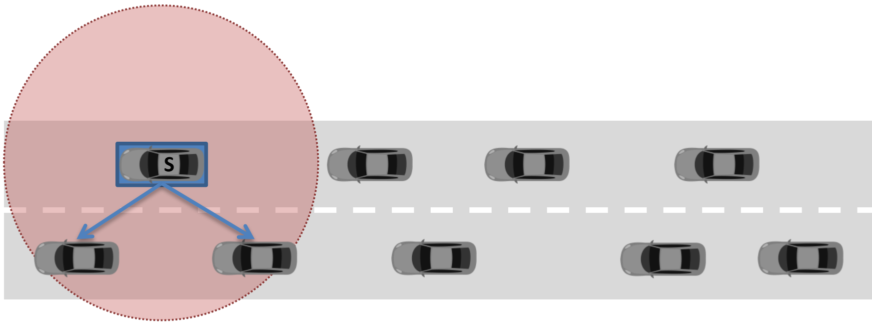


Figure 3.7: Example for beaconing communication (adapted from [1]). The vehicle marked in blue in the figure sends a link layer broadcast message with data about the own vehicle like position, heading, and velocity. This message is received by all adjacent vehicles in communication range and is not further rebroadcast. The communication range is marked as a red circle in the figure.

#### Description

Beaconing is a service to exchange information between adjacent vehicles. Therefore, all vehicles periodically send the so called beacon messages to their neighbors. The time between two consecutive beacons is called beaconing interval. Beaconing is primarily used for neighbor discovery and monitoring. It typically contains the own geographical position, heading, velocity, and other information which can be used by the routing protocol or applications.

Beacons can also be used to exchange information over multiple hops. For example, by including a list with the own already discovered neighbors into such a beacon message, it is possible to gather two-hop neighborhood information. Moreover, this way data can be disseminated over longer distances. Because the periodic dissemination of messages over longer distances increases the communication overhead significantly, it requires aggregation techniques to enable an efficient message dissemination via beaconing over multiple hops.

#### Communication Mechanism

Beaconing is implemented by a periodic IEEE 802.11p link layer broadcast to all nearby vehicles in communication range. Therefore, it is a best-effort service with no guarantees about delivery success and which nodes exactly receive a message. The beaconing interval is influenced by many parameters, e.g. the speed of the own vehicle, applications latency requirements and topological position of the vehicle. Typically, the highest beaconing frequency is around 10 $Hz$ [131, 132, 133, 134] (mandatory for safety applications with low latency requirement). But in a traffic jam for example, where the vehicle velocities are around zero, it is sufficient to send beacons at a much lower rate, down to one message every few seconds. Because of these frequency differences caused by different contextual properties, there are also several approaches to adopt the beaconing frequency based on such properties [135, 136, 137, 138, 139, 140].

#### Addressing

Beaconing addresses all adjacent vehicles in communication range. It is thus a multicast addressing scheme where the multicast group is implicitly defined by the topological vicinity of neighboring vehicles. A new vehicle enters the multicast group by physically moving into communication range and also through physical movement a vehicle leaves this group.

#### Trigger

Beaconing messages are strictly periodic, thus they are continuously sent at a specific beaconing interval. However, it is also possible that an event initiates a periodic message (e.g. a broken vehicle which periodically sends a message about its status to warn approaching vehicles), but such information can be typically packaged into the standard beaconing messages.

#### Directionality

Beaconing is strictly unidirectional, this is inherited by the IEEE 802.11p link layer broadcast mechanism.

#### Dissemination Range

Beaconing is used for short-range communication, typically for the exchange of one-hop sometimes of two-hop information. Nevertheless, beaconing can be used for information dissemination over middle and long distances. For this case aggregation schemes can be applied to significantly reduce the communication overhead caused by the periodic dissemination of information over such large distances.

#### Applications

There are many applications which can be implemented by means of beaconing. The short-range application classes *Collision Avoidance*, *Assistance and Cooperative Movement*, and

*Enhanced Driving* are using such a periodic multicast communication mechanism. Furthermore, the mid-range applications In-Vehicle Amber Alert (IVAA), Point-of-Interest Notification (PoIN), and Stolen Vehicles Tracking (SVT) can be implemented by dissemination atomic information through beaconing over a few hops. A typical application which makes use of dissemination of aggregated information through beaconing over large distances is the Intelligent Traffic Flow Control (ITFC) application. In that application vehicles cooperatively collect and spread aggregated information about traffic conditions over long distances to enhance the driving experience.

Additionally, beaconing is also a precondition for many routing protocols. It serves for neighbor discovery, establishment of routing tables, and other important routing related aspects. For this reason, beaconing can be regarded as a basic service for VANETs.

### 3.5.4 GeoCast

GeoCast is besides beaconing the second major multicast communication scheme for VANETs. This communication pattern is detailed in the following.

#### Description

One of the main purpose of VANET applications is the instant dissemination of warning messages about hazardous situations to approaching vehicles. For example after an accident, the involved car broadcasts a warning message rearward, thus the drivers of approaching vehicles are informed in time. The drivers gain valuable time, and therefore, they can slowdown or stop their vehicles, this way avoiding another dangerous situation. If such drivers are informed early, they may even take an alternative route, thus completely drive around the accident and this way avoiding a traffic jam.

Therefore, by warning the drivers in time, the road safety can be enhanced considerably. The obvious way to inform approaching vehicles is to flood a message into a road segment in which the vehicles would benefit from the disseminated information. This area is called ZoI and marks the boundaries of the flooded region. Because in VANETs this region is specified by geographical coordinates by the message initiator, this communication mechanism is called *Geographical Broadcast*, *Geobroadcast*, or – the term used in this work – *GeoCast* [112, 141, 115, 114, 142, 143].

#### Communication Mechanism

A GeoCast a message has to be delivered to all nodes residing inside a geographical region. Therefore, the initiator of a GeoCast messages specifies this ZoI in that message and sends

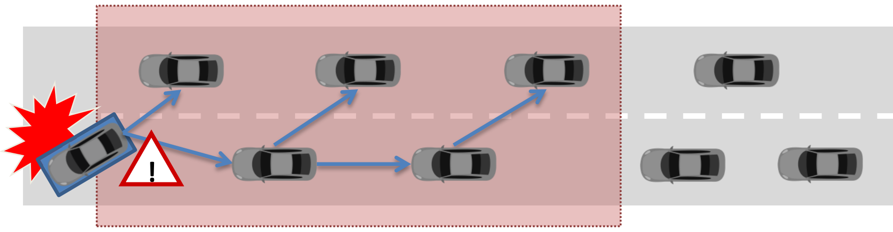

Figure 3.8: Example for GeoCast communication (adapted from [1]). A broken down vehicle (marked in blue on the left side of the image) initiates a broadcast message about the hazardous situation. This message is disseminated via multiple hops to inform all vehicles in the specified destination region. This geographic region is marked as a red square in the figure.

it to all vehicles residing inside that zone. The simplest approach to reach all vehicles is to flood that message inside this region, i.e. every node inside that region retransmits the warning message exactly once by performing a link layer broadcast.

The flooding dissemination scheme is very easy to implement, but it has a major disadvantage: many redundant messages are sent – especially in dense networks – which may lead to the so called *Broadcast Storm Problem* [119, 67]. Therefore, more efficient broadcast schemes were developed, which enable a more efficient information dissemination. For an overview of such protocols see e.g. [119] and [66], and Chapter 4 where this topic is discussed in detail.

#### Addressing

GeoCast addressing is a special form of multicast. As in multicast, the message is addressed to a group of nodes. The difference is the group membership mechanism: in multicast a node explicitly has to be registered to a multicast group, whereas in GeoCast the group membership is implicitly defined by the geographical position of nodes and the addressed region. Therefore, an initiator of a GeoCast message specifies a target region geographically, and that message is the delivered to all nodes residing inside that region.

### Trigger

There is a wide spectrum of VANET applications using this communication scheme. Therefore, GeoCast message dissemination can be triggered by a system event, by a user, and also periodic dissemination is possible. But the majority of the applications use GeoCast upon the occurrence of an event, such as a dangerous traffic condition.

### Directionality

The GeoCast communication scheme is strictly unidirectional, there is no use-case to establish a communication dialogue between the initiator of a GeoCast message and the addressed group members. Also from a network perspective, the communication overhead would be unproportional high compared with the resulting benefit, thus making such bidirectional communication unfeasible.

### Dissemination Range

This information dissemination scheme is used for applications which require medium and long distance communication. For short-range application the already discussed beaconing scheme can be used, thus GeoCast is not relevant for these applications. The dissemination range heavily depends on the efficiency of the applied protocol to broadcast the message in the destination region.

### Applications

One of the major use-case for GeoCast is the medium dissemination range application class *Abnormal Traffic and Road Conditions*. It consist of applications that intend to inform approaching vehicles to avoid a hazardous situation. *Public Safety* is another group of applications that uses GeoCast (including all applications but EVSP). Furthermore, also the PoIN from the application class *Mobile Services* makes use of GeoCast communication. Besides applications with medium dissemination range, there are also applications with a long dissemination range requirement using GeoCast. For example, the dissemination of the user query of the Query-based Parking Places Locator Service (QPPLS), Point-of-Interest Query (PoIQ) and TIQ applications could be realized this way. Another example is the Cooperative Traffic Jam Detection (CTJD) application.

## 3.6 Advanced Communication Patterns

Considering the application classes from a network perspective, it can be stated that the GeoCast, beaconing, unicast, and anycast communication patterns are the building blocks for those applications. Based on these basic patterns, more advanced communication schemes can be built which can be used to meet specific application requirements.

So for example, if an application needs to perform a GeoCast to a distant ZoI, then that message first needs to be routed to that distant region, before the broadcast inside that zone can be started. This special case of GeoCast is denoted as *Remote GeoCast*.

Another example is the periodic multi-hop dissemination of traffic and road status related information. Applications which require such a multi-hop dissemination need to apply some efficient aggregation techniques to overcome the limited bandwidth problem (c.f. [77, 144]). This scheme is called *Aggregated Information Dissemination*.

Another such advanced information dissemination scheme represents the *Cluster-based Information Dissemination*. In this scheme, vehicles organize themselves into clusters based on their similarity of specific criteria like geographical position, velocity, etc. Each cluster has a homogeneous view of the surroundings and has a cluster head which has a coordination role.

These advanced communication mechanisms are described in the following subsections.

### 3.6.1 Remote GeoCast

Remote GeoCast is a combination of the two basic communication patterns anycast and GeoCast. This combined communication mechanism is shown in Figure 3.9 and is detailed in the following.

#### Description

The purpose of Remote GeoCast is to disseminate a message into a distant region. For example, a user initiates a query to gather actual and accurate traffic information of a road segment several kilometers away. Based on that information, the user decides to take the forthcoming exit or to stay on the actual route. Regarding the communication overhead, it would be not practicable to perform a flooding of maybe several 10 kilometers of road and gather atomic information from the vehicles inside the flooded region. Therefore, it is much more beneficial to use anycast to route the query to that distant region, and upon reaching that region to use GeoCast to disseminate the query.

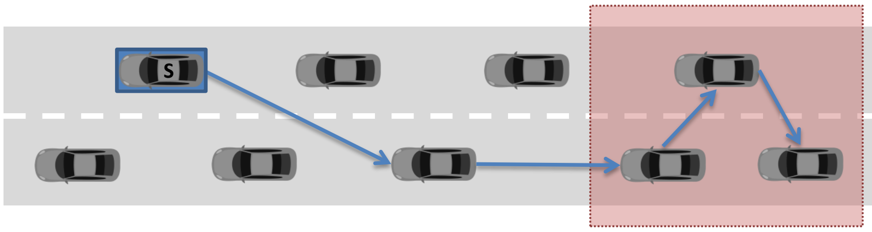


Figure 3.9: Example for Remote GeoCast communication. A vehicle (marked in blue on the left side of the image) initiates a broadcast message with a distant region as a geographical address (marked as a red square). This message is transported hop-by-hop towards the target region using the anycast dissemination scheme. Upon reaching that region, the message is flooded into that region using the GeoCast scheme.

#### Communication Mechanism

Remote GeoCast is the combination of anycast and GeoCast. Therefore, it can be divided into two phases:

- *Transport Phase*: The remote GeoCast message needs to be transported towards the target region. Therefore, anycast is used, i.e. the message is routed hop-by-hop towards that region, using IEEE 802.11p unicast communication. When the message reaches the target region, it is delivered to the first vehicle residing inside that region. That vehicle initiates the second phase of this protocol.

- *Broadcast Phase*: A vehicle which received the anycast message from the first phase, performs a normal GeoCast to broadcast the message to all other vehicles inside that region. Therefore, an efficient broadcast dissemination protocol is used (as is the case of GeoCast outlined in Section 3.5.4 and detailed in Chapter 4) which is based on IEEE 802.11p broadcast communication.

#### Addressing

GeoCast as well as anycast are using a geographic region as an addressing scheme. Therefore, it is obvious that also the Remote GeoCast communication mechanism uses this addressing scheme.

#### Trigger

This communication scheme is an extension of GeoCast, and therefore, the same triggers do apply. For the majority of applications the Remote GeoCast is triggered by an event or by a user.

#### Directionality

Remote GeoCast uses unidirectional communication. However, as the user-initiated information query application shows, there are use-cases where an answer message is routed back to the initiator of the Remote GeoCast message. In that example, the vehicles in the target region gather traffic information, which is then routed back to the initiator by using unicast communication. But this answer message uses a completely other communication type (unicast) and it is transmitted deferred. Thus, it has no tight correlation with the original message and therefore, it has not the character of a dialogue between two communication parties.

#### Dissemination Range

The dissemination region is not necessarily increased compared with GeoCast, but that region can be geographically distant from the initiator of the message. Therefore, the dissemination range is increased compared with simple GeoCast, thus this scheme support both middle and long dissemination range applications.

#### Applications

Potentially all applications using GeoCast can also benefit of the remote version of that communication mechanism. Typical applications are the query-based information gathering approaches like PoIQ, QPPLS, and TIQ. But also other applications, like PoIN, Parking Places Locator Service (PPLS), and CTJD could benefit from this extended GeoCast communication.

### 3.6.2 Aggregated Information Dissemination

The wireless medium used by IEEE 802.11p is a scarce resource and many devices are competing to access and exchange data. Therefore, it is of eminent importance for VANET applications to consider the message generation rate, the message size, the communication distance, and the number of addressed vehicles. If applications require a periodic dissemination of information over large distances to and by all participating network members, then aggregation techniques will have to be applied to enable an efficient information dissemination with these parameters. Such Aggregated Information Dissemination is described in the following and is depicted in Figure 3.10.

#### Description

The idea behind information aggregation is that many applications do not need accurate, atomic information – i.e. information in the form as it was produced, thus unchanged. For example, if a driver wants to know the driving speed from point A to B, then it is not important to have the exact speed values of all vehicles between these two points on the road. If all vehicles would had identical velocities, then it would be enough to communicate one velocity value and not that of all vehicles. Therefore, by information aggregation spatially correlated atomic values are averaged and merged, thus significantly reducing the communication overhead.

An example is the ITFC application: Vehicles periodically exchange their velocities through beaconing. If adjacent vehicles have similar velocities, then these values could be averaged and further disseminated. Thus, such an aggregated value corresponds to the real speed values of many vehicles moving on a road segment. The average speed values of multiple road segments could be further averaged and information about traffic conditions disseminated over longer distances.

It is clear, that with increasing distances the accuracy of such aggregated information declines. But as we have seen, for some applications such imprecise information is still enough to enable a proper function of that application. Moreover, with increasing distances the importance of information accuracy declines, i.e. it is inversely proportional to the distance. The gain through the possibly extreme large dissemination ranges is very high, therefore, a high user benefit can be obtained by applying such aggregation schemes for VANETs.

There are many aggregation algorithms both for MANETs and VANETs. In MANETs the primary goal of data aggregation is to reduce the energy consumption. But the basic concepts applied for that energy constrained network can be adopted for VANETs. For an overview of aggregation schemes in MANETs see e.g. [145, 146, 147, 148, 149]. For VANETs the main focus in data aggregation is on cooperative traffic information systems (see [77, 150] for an overview).

MANETs typically use a tree-based (e.g. [151, 152, 153] ) or cluster-based (e.g. [154, 155]) approaches for data aggregation. The maintenance of a tree- or cluster-based hierarchy is very challenging for dynamic networks, therefore a structure-free approach was introduced by Fan et al. in [156, 149]. In VANETs both hierarchy-based and structure-free approaches do exist [74, 157, 88, 121, 158, 159, 77, 144]. Aggregation structures are typically organized in geographical regions for VANETs. The structure-free approaches have the main advantage, that values are not only aggregated by their geographic position but based upon their correlation to each other, be it in space, time, or other application specific dimension.

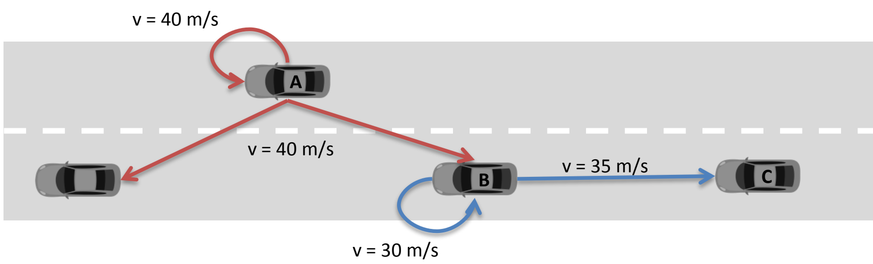


Figure 3.10: Example for Aggregated Information Dissemination. This example shows the basic idea behind data aggregation. Vehicle A retrieves its velocity from onboard sensors. Because at this time being the only velocity information, vehicle A disseminates this atomic information to its neighbors. Vehicle B receives this velocity information, and it enriches it with its own sensor data. In this example a very simple aggregation function is used, the two velocity values are simply averaged. This new computed data is then sent to vehicle C, probably with a road segment information for which the average speed was computed. Vehicle C can then perform the same steps and further disseminate the average speed information.

### Communication Mechanism

Because the extended dissemination ranges used by applications based on aggregation, the latency constraint is not that relevant as for short- and mid-range applications. A vehicle needs maybe several minutes or even longer to cover the dissemination distance. Therefore, there is no need for the immediate dissemination of such messages, they rather are packed into the beacon messages which are scheduled periodically. This way, such applications periodically exchange the needed information with their neighbors, perform the aggregation algorithm, and finally disseminate the updated information in the next beaconing round again.

#### Addressing

Typically, information aggregation incorporates the data into the beacon messages. Therefore, the addressing scheme used is the same as of beaconing. It is multicast addressing and the multicast group members are all adjacent vehicles in communication range.

#### Trigger

Because aggregated information dissemination is based on beaconing, the dissemination of aggregated data occurs periodically. The data is incorporated into the beacon messages and is sent out periodically to all adjacent vehicles in communication range.

#### Directionality

The aggregated data is sent out with the use of IEEE 802.11p broadcast, and is therefore unidirectional. Bidirectional communication is not required by applications based on aggregation and would increase the communication overhead unnecessarily.

#### Dissemination Range

The aim of Aggregated Information Dissemination is to greatly enhance the dissemination range of applications. Therefore, especially long-ranged applications are supported by this information dissemination scheme.

#### Applications

Most applications with long communication range requirement make use of Aggregated Information Dissemination. The most common application is the ITFC application, where the vehicles cooperatively exchange aggregated traffic relevant information. This information is then used to enhance the driving efficiency on the roads by providing them to the navigation system and to the driver. But also the detection of free parking places and cooperative traffic jam detection can be based on this information dissemination scheme.

### 3.6.3 Cluster-based Information Dissemination

Another advanced dissemination scheme is the Cluster-based Information Dissemination. The idea is that nodes with similar properties are grouped into clusters. Every cluster has a cluster head which undertakes management functionality and thus coordinates the other cluster members. Nodes which are in communication range with more than one cluster are the so called gateways and are responsible for the exchange of information between clusters. Figure 3.11 shows this communication pattern and is detailed in the following.

### Description

The idea of clustering is to abstract several nodes – which are located geographically adjacent – to clusters, thus introducing a topology overlay. Typically the members of a cluster have a homogenous view of the surrounding and the nodes are grouped based on similar properties. In this way, all nodes of a cluster share one information base, and therefore, it does not matter if all nodes of a cluster disseminate a message or only one of them. The information transmitted is still the same, but the communication overhead can be reduced significantly. To achieve this, a cluster head takes a management role to coordinate the time points and the kind of information communicated by the cluster members and to synchronize the information base for all members.

A node's cluster membership is determined by the clustering algorithm which can be based on several properties of that node. The cluster group membership of nodes is changing over time due to node mobility [160]. Therefore, the most important criteria for such a cluster membership in VANETs is the vehicles' mobility in order to achieve stable clusters over time [161]. I.e. vehicles with similar velocity, heading, driving routes, and position should be grouped together, because there is a high probability that such vehicles remain in the same cluster over time [162].

A cluster can have different sizes, measured by the hop distance from a cluster head to its cluster members. For example, in one-hop clustering the cluster members are in communication range to their cluster head. Thus, in n-hop clustering that distance can be up to n-hops. Such n-hop clusters introduce some additional challenges because a message from a cluster head always needs to be disseminated multi-hop to all cluster members.

### Communication Mechanism

In a clustered network two communication types can be distinguished: intra- and inter-cluster communication.

- *Intra-cluster Communication:* The communication inside a cluster, thus between cluster head and its members. Typically, a cluster head uses multicast communication to broadcast a message to all cluster members. Depending on the cluster size, this can be

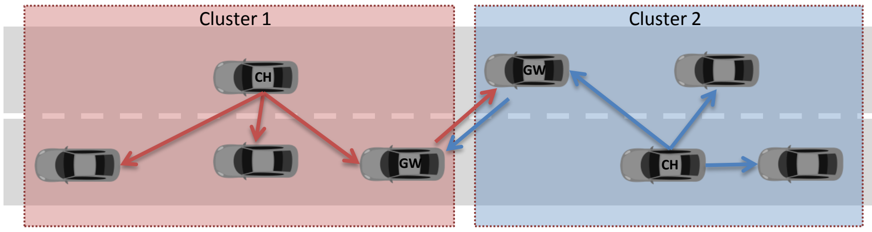


Figure 3.11: The figure shows two clusters (1 and 2). Both clusters have exactly one cluster head (CH) which has a coordinating role. They send out control messages to their cluster members. Communication between clusters takes place through so called gateway nodes (GW). This way inter-cluster information dissemination is realized.

achieved through single-hop broadcast for one-hop cluster or through multi-hop broadcast for larger ones. Therefore, beaconing could be used to periodically disseminate cluster coordination messages (which are needed to keep the clusters up to date) and application specific information. On the other hand, a cluster member typically uses unicast communication to exhchange information with its cluster head.

- *Inter-cluster Communication:* When the applications' communication range requirement exceeds the cluster size, the communication mechanism is required to exchange information between different clusters. To achieve this, so called gateway nodes are used, which are located on the border of a cluster and are in communication range with gateway nodes of adjacent clusters [163]. A cluster head sends a message to its gateways, which then retransmit that message to gateways in neighbor clusters. These gateways in turn forward the message to their cluster heads which are again responsible for the dissemination to all member nodes of their cluster. For the inter-cluster communication both unicast and multicast can be used.

Because clustering represents a very complex communication type and moreover, there are many different clustering schemes with different communication requirements, the communication mechanisms used in clustering are manifold. As we have seen, for intra-cluster cluster head to member communication beaconing can be used but also the use of an event-based multi-hop broadcast is possible. Unicast can be used for the communication between cluster members with their cluster heads but for this case also a broadcast- or beaconing-based communication is possible. Moreover, clusters are formed based on similar properties of their members and the membership functions are similar to aggregation techniques. Thus, cluster topologies by nature support data aggregation and there are plenty of such aggregation schemes [155, 164, 165, 78, 166, 167, 158]. It can be concluded, that for Cluster-based Information Dissemination almost all communication mechanisms can be applied. This holds also for the addressing, the trigger, the directionality, the dissemination range, and the applications.

## 3.7 VANET Characteristics

In the last sections, we have noted the building blocks for VANET dissemination protocols. Before going into the details of such protocols, we briefly summarize the VANET characteristics[1]. Together with the discussed application properties, they reveal some important implications on the communication protocols.

### 3.7.1 Node Mobility

Vehicles on highways potentially travel at very high speed. Thus, the communication timeframe between these vehicles can be very short. Moreover, high node velocities cause more frequent topology changes resulting in outdated neighbor tables. Thus, when a protocol relies on such a table, the forwarding decision may be incorrect due to old or nonexistent entries in this table.

### 3.7.2 Dynamic Topology

Characteristic for VANETs is a very high dynamic network topology. The reason therefore is twofold: First, the node density ranges from very sparse and partitioned networks e.g. on rural freeways or late night hours to very dense networks at rush hours and traffic jams. Thus, the number of neighbor vehicles in transmission range can vary from zero up to hundreds of nodes. Second, node mobility can range from static nodes in traffic jams up to very high velocities on free highways. This implies that a routing protocol has to overcome sparse and partitioned as well as dense scenarios, which are subject to rapid changes over time due to node mobility.

[1] Adapted from [1].

### 3.7.3 Wireless Communication

The dissemination of information in a VANET is based on a wireless medium which represents an error-prone and scarce resource in the network. Especially in dense network scenarios, where many cars compete for the wireless medium, the limited bandwidth constitutes a severe problem for the routing protocol. Therefore, an efficient and robust information dissemination protocol is of eminent importance for a successful deployment of VANET applications.

### 3.7.4 Delay Constraints

As outlined in Section 2.3, most of the event-triggered applications are delay critical. This means, they rely on information dissemination mechanisms, which allow the delivery of information with minimal delay. Thus, a dissemination protocol designed for such applications has to forward safety critical information immediately without introducing considerable delay e.g. for routing purposes.

### 3.7.5 Geographical Addressing

In VANETs typically a geographical addressing method is used suitable for most envisioned applications. This means that a broadcast is not performed network wide (which is simply not possible due to the potential size of several million nodes in the network), but is limited by a geographic region (see the description of GeoCast in Section 3.5.4 for details). Similarly, unicast protocols make use of position information available via GPS receiver for route decisions.

### 3.7.6 Mobility Patterns

Another important aspect of VANETs is that vehicle movements are constrained by the road topology. This means, node movements obey mobility patterns imposed by the road network. Thus, node mobility is predictable and can therefore be utilized by routing protocols to enhance the dissemination performance. Roughly three main classes of movement patterns can be distinguished, which directly influence the degree of predictability of node movements: inner city roads, rural roads, and highways.

### 3.7.7 Beaconing

As shown in Section 3.5.3, beaconing is a fundamental communication form for a wide range of applications. Thus, it can be assumed that this periodic exchange of information with adjacent vehicles will be present in vehicular networks. Therefore, such exchanged information – e.g. in form of neighbor tables – can be used by a dissemination protocol without introducing additional communication costs.

### 3.7.8 Pseudonym Change

By communicating information, vehicles reveal personal information which results in a severe privacy problem [168, 169, 170]. To solve this problem, vehicles are supposed to communicate using pseudonyms which they change at a given frequency [171, 172, 173]. But by changing its pseudonym, a node may become unknown to a communication participant. Moreover, a node may be inserted into the neighbor table multiple times under different pseudonyms. Having such incorrect neighbor entries, routing decision cannot be met correctly anymore. Thus, pseudonym changes may greatly affect the communication protocol if it uses such information [174, 175].

| **Characteristics** | **Implications** |
|---|---|
| *High Mobility* | Outdated neighborhood information and short communication periods. |
| *Dynamic Topology* | High variance in network density and node velocity: partitioned networks vs. traffic jams. |
| *Wireless Communication* | Limited bandwidth and error-prone wireless communication. |
| *Delay Constraints* | Messages need to be broadcast immediately without introducing any delay. |
| *Geographical Addressing* | Position information of vehicles are needed and GeoCast is an important communication mechanism for safety applications. |
| *Mobility Patterns* | Protocols can benefit from predictable mobility patterns to enhance their rebroadcast decision. |
| *Beaconing* | Beaconing is used by a wide range of applications, therefore it can be also used by network layer protocols without introducing additional communication costs. |
| *Pseudonym Change* | Pseudonym changes result in incorrect neighbor tables. Thus, pseudonym changes introduce a new challenge to VANET protocols which rely on such information. |

Table 3.2: VANET characteristics and their implications (adapted from [1]).

Table 3.2 summarizes the discussed VANET characteristics together with their implications. Based on these implications, a more exhaustive requirements analysis can be done in the next section.

## 3.8 Requirements Analysis

The diversity of VANET applications and the special network characteristics impose several nonfunctional requirements to the broadcast protocols. They are deduced from the previous sections and summarized in the following[2].

### 3.8.1 Scalability

The broadcast protocol has to cope with very dense networks like traffic jams in order to enable correct operation of safety applications in such scenarios.

### 3.8.2 Effectiveness

The broadcast protocol has to assure that all nodes (or a percentage of nodes, defined by the application) in the destination region receive the disseminated information.

### 3.8.3 Efficiency

Due to the limited available bandwidth, the broadcast protocol needs to eliminate message redundancy by minimizing the forwarding rate of messages. On the same time, the protocol has to assure the reception of a message by all nodes in a specific geographic region. This helps to avoid the broadcast storm problem ([119]) and enables the coexistence of multiple VANET applications.

### 3.8.4 Dissemination Delay

Safety applications require the immediate relaying of information without the introduction of any delay.

### 3.8.5 Delay-tolerant Dissemination

Because vehicular networks are subject to frequent partitioning, it is desirable to cache information in such scenarios and propagate them later when new vehicles are available in the

[2] Adapted from [1].

vicinity. Otherwise important information can be lost when the network in the destination region is not fully connected.

### 3.8.6 Robustness

The communication over the wireless medium is error-prone (or in the presence of pseudonym changes), nevertheless, the broadcast has to cope with packet losses in order to assure the correct function of vital safety applications.

It has to be noted that not all requirements can be met to a full extent because some requirements are contrary. So, for example, when minimizing the forwarding ratio to achieve a high efficiency, the requirement robustness cannot be fulfilled anymore because relaying nodes represent a single point of failure in this case. Thus, when a relaying node fails to forward a message (which is probable due to the wireless nature of the communication channel) the overall reception rate can also drop significantly. Therefore, in most cases an elaborate tradeoff between such requirements is needed.

## 3.9 Summary

This chapter gave an introduction to vehicular communications. It outlined the radio hardware used for such networks and the IEEE 802.11p protocol stack which provides the basic communication mechanisms to build VANET applications. The review of the literature about this topic showed that IEEE 802.11p works well for VANET applications under optimal conditions. But as discussed, IEEE 802.11p degrades seriously in term of latency and transmission range under NLOS situations, and most important, with increasing node density. Thus, especially dense networks are challenging for information dissemination protocols. Particularly broadcast protocols introduce themselves a significant communication overhead and therefore, it is very difficult to design efficient broadcast protocols which deliver messages reliably and efficiently even in very dense networks.

Furthermore, a brief classification of different vehicular communication types was given. This classification identifies three basic communication types: IVC, RVC, and HVC. The most benefit offers HVC, because it combines the two other communication types, and therefore, the advantages of both communication types can be utilized. Furthermore, we discussed that from a communication point of view, a RSU behaves as a vehicle with zero velocity. Therefore, in this work it is not differentiated between those two network participants, thus HVC is assumed if not other stated.

Next, VANET applications' communication requirements were translated to network attributes. The objective was to determine the network properties on top of IEEE 802.11p to fulfill these requirements. This way a set of network attributes was determined which then was used to define four basic communication mechanisms for VANET applications. These so called communication patterns are *unicast*, *anycast*, *beaconing*, and *GeoCast*. All applications discussed in Chapter 2 can be supported by these four fundamental VANET communication mechanisms. Moreover, these patterns can be further used to realize more advanced communication mechanisms. We identified three of such advanced communication patterns: *Remote GeoCast*, *Aggregated Information Dissemination*, and *Cluster-based Information Dissemination*.

Also the vehicular network characteristics were identified which should be considered by the dissemination protocols. These are special characteristics of VANETs, implied by the high velocities of vehicles on roads. This was followed by a summary of non-functional requirements relevant for the quantitative evaluation of such protocols. With the help of these metrics, the dissemination protocols can be evaluated by simulations and compared with each other. This is very important for the comparableness of different approaches and thus, to deduce the strength and weaknesses of such protocols.

As a summery we can state, that in this chapter the key communication mechanisms were identified to support VANET applications. It is obvious that these communication patterns are different in terms of realization difficulty and the number of applications they support. The more applications a communication pattern supports, the higher is the benefit of the deployment. As we have seen, the majority of the VANET applications require a broadcast information dissemination scheme, be it a one-hop broadcast (*beaconing*) or over multiple hops (*GeoCast*). In the following, the objective of this thesis is the evaluation of such multi-hop broadcast schemes. Besides the number of applications multi-hop broadcast schemes support, the rationales behind the focus on this topic are as follows:

- *Beaconing* is used especially by safety applications and – as shown in the next chapter – also by broadcast protocols to gather information of a car's neighborhood. The implementation of a beaconing service is trivial, the beaconing frequency which is the key parameter is directly derived from the applications' latency requirements and the own velocity. It can be regarded as a standard service in VANETs without research challenges from a communication point of view.

- Safety applications can be regarded as the driving force behind the utilization of VANETs. However, besides the Pre-Crash Sensing (PCS) application, *unicast* is not used by active safety applications. But more important, if an optimal route from the source to the destination is known, *unicast* will be the optimum in term of communication efficiency to deliver a message to a single destination. Thus, there is no challenge regarding the efficient dissemination, but route discovery and route maintenance over time in presence of the discussed network dynamics. For the route discovery in many reactive unicast protocols usually multi-hop broadcast is used as a basic service. See e.g. DSR [123], AODV [124], and LAR [176]. This additionally underlines the importance of an efficient broadcast-based information dissemination in VANETs. Route maintenance is not within the scope of this thesis.

- The advanced communication patterns discussed in this chapter are not further investigated for two reasons: First, they can be regarded as an overlay on top of the basic communication mechanisms of VANETs, representing an orthogonal enhancement. Second, clustering and information aggregation in VANETs are separate research areas. These investigations would go beyond the scope of this thesis.

# CHAPTER 4

# Broadcast Approaches

As we have seen, many Vehicular Ad-hoc Network (VANET) applications are based on Geographic Broadcast (GeoCast) communication which is realized as a geographically limited broadcast. Moreover, as discussed in the previous chapter, broadcast plays also an important role for the route discovery of several topology-based unicast routing protocols. Because of its relevance, in this chapter we conduct a thorough evaluation[1] of different broadcast approaches for vehicular networks.

First, we show an introduction to information broadcast in vehicular networks. This is followed by a detailed review of related work on this topic, together with a classification of different approaches. These broadcast classes are discussed in detail, thus contrasting the pros and cons of different approaches. Based on this classification, existing broadcast approaches are reviewed and their properties are compared. This literature review also includes the investigation of novel hybrid broadcast approaches and finally, this chapter is closed by concluding remarks.

## 4.1 Introduction

Broadcast of a message means its dissemination into a target region. Thus, we use it as a synonym for GeoCast, as introduced in the previous chapter. Applications use such a broadcast protocol to disseminate for example a warning message into a Zone of Interest

[1]Parts of this evaluation were initially published in [1].

(ZoI). By receiving such broadcast messages, vehicles could benefit from it, e.g. by avoiding dangerous situations.

The easiest way to implement a broadcast mechanism is the use of naïve flooding [177, 178, 179]. In flooding every node rebroadcasts a message exactly once (given that it is located inside the destination region), thus the message is flooded into the whole region. This means, upon receiving a broadcast message, a node checks if its position is inside the destination region and if it received the message for the first time. If both conditions are true, it rebroadcasts that message.

However, simple flooding is very inefficient. Consider a scenario, where $n$ vehicles are in the destination region and all are in communication range of each other. Because of this, only one link layer broadcast is enough to reach all vehicles. If all $n$ vehicles performed a rebroadcast it would result in $n-1$ redundant messages.

This message redundancy is the main disadvantage of flooding. Given the limited bandwidth of the wireless medium, an inefficient information dissemination scheme like naïve flooding leads to redundancy, contention, and collision, which is known as the *broadcast storm problem* [119, 180, 120].

To overcome these problems, more efficient broadcast protocols are needed for VANETs. For example, there are broadcast schemes which use neighborhood information to minimize the number of retransmissions or they rebroadcast a message only with some probability. The evaluation of such efficient dissemination schemes is the scope of this chapter. Before existing approaches are reviewed, the next section describes a classification of broadcast schemes in VANETs.

## 4.2 Classification of Broadcast Protocols

One of the first in-depth classification of broadcast approaches for Mobile Ad-hoc Networks (MANETs) was done by Williams and Camp in [181]. They identified four main classes: *Simple Flooding*, *Probability-based Methods*, *Area-based Methods*, and *Neighbor Knowledge Methods*, which are discussed in the following.

- *Simple Flooding*: Every node rebroadcasts a message exactly once, as described previously.

- *Probability-based Methods*: Probabilistic dissemination – also called gossiping – is similar to flooding, with the difference that a node not always rebroadcasts a message but only with a certain probability. This way, flooding can be seen as a special case of gossiping: the nodes rebroadcast a message with the probability of 100%. The goal of gossip protocols is to reduce the message redundancy by minimizing the number of rebroadcasts through the rebroadcast probability parameter [120, 182]. It is obvious, that this rebroadcast probability is dependant on the network density, thus for achieving efficient information dissemination, such parameters have to be adopted to the actual topology [183, 184]. Therefore, several adaptive gossip-based broadcast approaches were proposed, which adopt the rebroadcast probability dynamically [185, 186, 187, 117, 118].

- *Area-based Methods*: The rebroadcast decision of these approaches is based on the additional coverage area of a rebroadcast message. It means, upon receiving a message, a node calculates the area it would additionally cover by a subsequent retransmit. Based on the size of this area the protocol decides to perform a rebroadcast or not. The additional coverage area is depending on the distance between the node's position which performed the previous transmission and the actual node which decides about the retransmission of that message. It varies from almost zero (the two nodes' positions are close to each other) and up to 61%, compared with the complete dissemination region of a node's transmission [119]. This area can be determined by the distance between those two nodes, by their position received via Global Positioning System (GPS), and also based on topology information. Therefore, the additional coverage area is used by a wide range of approaches: by gossip-based protocols to determine the forwarding probability [185, 118], by counter-based and location-based rebroadcast schemes [183], and by approaches which introduce a retransmission timer based on the additional coverage as e.g. in Contention-based Forwarding (CbF) [188].
- *Neighbor Knowledge Methods*: These broadcast schemes make use of neighborhood information to derive rebroadcast decisions. Actually, the majority of broadcast protocols are using such topology information, especially in the context of MANETs. The reason is that by such topology knowledge very efficient forwarding decision can be met. Well-known approaches are Flooding with Self Pruning and Dominant Pruning [189], Multipoint Relaying (MPR) [190], and the Scalable Broadcast Algorithm [180]. There are also protocols which according to this classification belong to another broadcast class but still use neighbor knowledge information. For example, the Position-based Gossiping (PbG) scheme makes additionally use of vehicles' position information [117], and also the counter-based and location-based schemes from [183] use neighborhood information.

More recent works on broadcast classification adopted this thorough analysis from Williams and Camp and refined it with new properties (cf. e.g. [3, 191, 192, 193, 194, 195, 196, 197]).

Although such a categorization is useful to evaluate and discuss the properties of broadcast protocols belonging to different classes, it has a significant drawback. Such an exclusive differentiation into rigid classes is not practicable for many broadcast protocols. We argue that many protocols are not belonging to one fixed class, but combine the properties from different classes. This is the case for example with the additional coverage broadcast class. Typically the additional coverage is determined by position information. But such an additional coverage can also be deduced from the local network topology, e.g. using two-hop neighbor information. Therefore, such protocols are both, additional coverage and neighbor-knowledge-based approaches. Therefore, we argue that topology, position, and other information are rather properties of broadcast protocols. Another example is the mentioned Advanced Adaptive Gossiping (AAG) protocol which is a gossip-based approach but also uses neighbor knowledge.

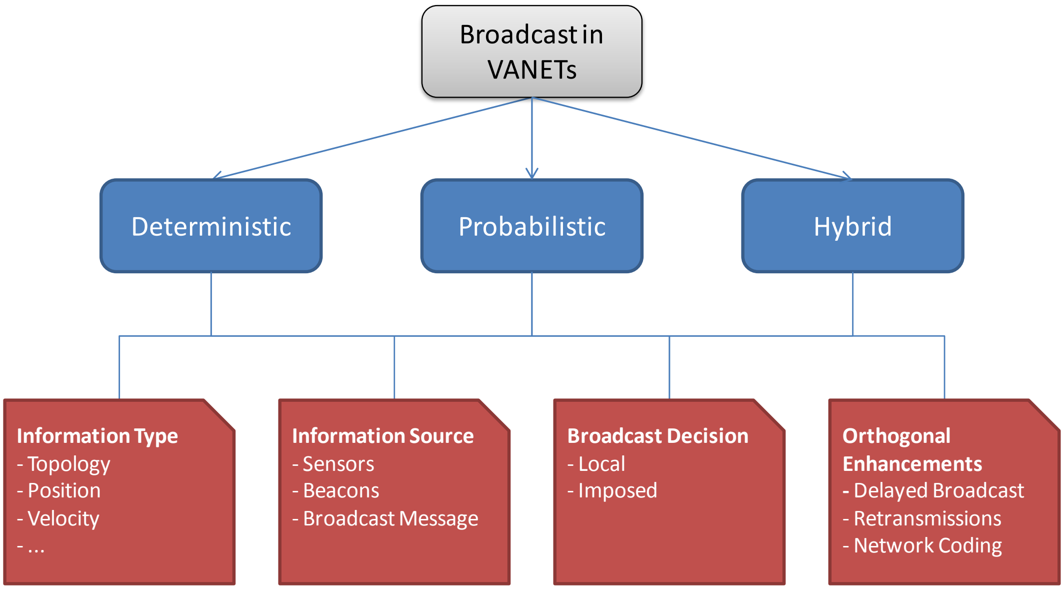


Figure 4.1: Classification of vehicular broadcast approaches.

For this reason, we propose a classification based on three basic broadcast types, which can in return have several properties, which we are going to discuss later. These three basic VANET broadcast classes are *deterministic*, *probabilistic*, and *hybrid* broadcast and are illustrated in Figure 4.1.

- *Deterministic Broadcast*: Characteristic for these approaches is that the forwarding decision is based on several criteria without introducing a random behavior by the dissemination protocol. More precisely, given the set of input parameters $P_{tn} = \{p_1, p_2, \ldots\}$ at a time $t_n$ for the forwarding decision function $f(P_{tn})$ the following equation is fulfilled for deterministic approaches: $\forall n, m(P_{tn} = P_{tm} \rightarrow f(P_{tn}) = f(P_{tm}))$. The forwarding decision is typically based on local network topology knowledge but also additional information (e.g. position and velocity) can be used to enhance the rebroadcast decision.

- *Probabilistic Broadcast*: In contrast to deterministic broadcast, probabilistic approaches introduce an implicit randomness, thus the above equation is not necessarily true anymore. In this scheme, a node rebroadcasts a message with a certain probability. This probability can be fixed a priori (*Static Gossip*) or adapted dynamically (*Adaptive Gossip*). For the adaptation of the broadcast probability, probabilistic approaches typically use information from overheard messages and local sensors. Thus, such approaches are strictly local-decision-based, i.e. a node decides on its own with which probability to broadcast a message. If additional information (e.g. topology knowledge) is used then we refer to hybrid broadcast approaches as detailed in the following.

- *Hybrid Broadcast*: Characteristic for probabilistic approaches is that they are easier to implement – in terms of protocol complexity – than deterministic ones and through that random behavior they provide implicitly more robustness. On the other hand, without any other additional mechanisms they are not as efficient as deterministic approaches [1]. Therefore, especially in a networks with high network dynamicity like VANETs, a third class of protocols gains importance intended to combine the advantages of both protocol classes and referred to as *Hybrid Broadcast* approaches [198, 1]. Characteristic for this group is that they use concepts from deterministic approaches (e.g. two-hop neighbor knowledge) to adaptively calculate adequate broadcast probabilities.

Independent of these three broadcast classes, each dissemination scheme can have several properties, which define key characteristics of that protocol. Knowing such attributes and their implications, it allows a more thorough analysis of the properties of a protocol. Therefore, we consider such information as key attributes which are used in our classification. This attributes are discussed in the following.

### Information Type

This property indicates which information types are used by a broadcast protocol. For example, the deterministic forward decision can be based upon two-hop neighbor knowledge or the broadcast probability can be based on the number of overheard rebroadcasts of a message. In vehicular networks, broadcast decisions can be based on additional information like geographical position, velocity, and heading of vehicles. For example, a node could calculate the distance to the last hop of a received broadcast message. Based on that distance, the additional coverage could be calculated which in turn is the input parameter for the rebroadcast decision function.

If a protocol uses neighbor knowledge (e.g. over one-hop or two-hop), such information typically needs to be exchanged periodically (by so called beacon messages) at a frequency depending on nodes' velocities. This results in higher communication overhead due to the periodically exchanged data but allows on the other hand very efficient rebroadcast decisions. In dynamic networks this kind of protocols may degrade in performance with increasing node velocity due to outdated neighbor tables.

### Information Source

There are three types of information sources from where the protocols' input parameters can be retrieved:

- *Onboard sensors*: Vehicles are equipped with plenty of sensors from which local information can be received. Including the vehicles geographical position, velocity, heading, acceleration, etc.
- *Beacon Message*: Information sensed by onboard sensors together with topology information can be disseminated periodically by using a beaconing service. This way, besides data from own sensors, additional information from vehicles in one or even two-hop neighborhood can be used to enhance the forwarding decision. This is at the expense of additional data volume needed to be transmitted periodically.
- *Broadcast Message*: Also the broadcast message can be applied to piggyback broadcast control data which is used to determine more efficient broadcast decisions. It is obvious, that this increases the message size, thus there is a higher probability for message losses and more bandwidth is used.

### Broadcast Decision

In *local decision* protocols, a node itself decides on reception to rebroadcast the message or not. Contrary to that, *imposed decision* protocols incorporate the identification of relay nodes in the broadcast message. Thus, a rebroadcasting node has to decide which of its one-hop neighbors have to forward the message. This requires a two-hop neighborhood knowledge of the surrounding topology, which typically introduces additional communication overhead to maintain such neighbor tables. Especially in networks with high dynamicity this may cause significant performance degradation of the broadcast protocol. Therefore, in contrast to the imposed decision, the local decision is a desired property of protocols especially in highly dynamic environments like VANETs.

### Orthogonal Enhancements

Although the main goal of broadcast protocols is to minimize the forwarding ratio in order to eliminate unnecessary rebroadcasts, the information gathered by the protocol can also be used to realize some orthogonal enhancements. They increase the efficiency or reliability of the underlying protocol. Such an enhancement can be used independently of the applied broadcast protocol and other orthogonal enhancements. We distinguish three such features to enhance the broadcast performance in three different ways.

- *Delayed Broadcast*: This enhancement introduces a delay before rebroadcasting a message defined by a delay function (randomly or according to some property of the node like distance to the sender). The delayed rebroadcast is useful when nodes overhear the communication channel and gather information about rebroadcasts from other nodes, thus allowing a more efficient rebroadcast decision. An example for this type of protocol is the Dynamic Delayed Broadcasting (DDB) introduced by [191].

- *Retransmissions*: Because GeoCast is implemented by the use of IEEE 802.11p link layer broadcast, the transmission of a message is not acknowledged and is therefore unreliable (cf. 3.2.2). Because of this, it is important that the dissemination protocol itself implements a mechanism to enhance the reliability in order to achieve the application level requirement regarding the effectiveness of the protocol. One possibility is to rebroadcast the message after a certain delay. The rebroadcast decision as well as the delay can be based on information overheard from the wireless channel and other data like topology information. Consider e.g. an imposed decision protocol, where the sender of a message defines the relaying nodes by piggybacking this information into the broadcast message. This node could wait a certain timeout and check if all those relaying nodes performed a rebroadcast of that message. If some rebroadcasts were missing, the node could retransmit the message again. This way a certain delay is introduced, but the reliability can be enhanced significantly. Another scheme to enable such a retransmission is the so called counter-based scheme introduced in [119].

- *Network Coding*: Another orthogonal extension is network coding [199]. The idea is to allow intermediate nodes to combine several incoming packets in order to reduce the number of retransmissions [200, 201]. Consider e.g. a scenario with three nodes $A$, $B$, and $C$. Assume node $A$ received a message from both, node $B$ and node $C$. Thus, it should retransmit both messages. Applying network coding, node $A$ could encode both messages into a single message using e.g. a simple XOR-based algorithm. Thus, it retransmits only one encoded message and upon reception, the nodes $B$ and $C$ decode it through the XOR operation using their own original message. This way network coding can reduce the number of retransmissions significantly and it can be applied for both, deterministic ([200]) and probabilistic ([202]) broadcast.

Clustering, in contrast to other classifications, is not considered as a basic attribute of protocols, but is more an aggregation of other properties. A standard clustering scheme utilizes normally topology information to build the clusters and cluster heads apply the imposed decision scheme to designate the relays. This holds also for more advanced clustering schemes, thus they utilize a combination of the key protocol attributes defined above.

This section provided a basic classification of broadcast protocols for VANETs and mentioned several attributes of such protocols. Based on this classification, the related work is discussed in the following section.

## 4.3 Related Work

As we have seen, due to the diversity of VANET applications and the special network characteristics, the design of an efficient broadcast protocol is a challenging task. Therefore, many approaches do exist to enable an efficient information dissemination into a geographic region.

In this section we review existing broadcast mechanisms designed to perform well in highly dynamic environments like VANETs. We not only consider VANET protocols here, but cover also protocols for mobile ad-hoc networks. Thus, we present an up-to-date and broad discussion of broadcast protocols from multiple domains. The subsequent subsections are organized according to our classification of broadcast mechanisms from the previous section.

### 4.3.1 Deterministic Broadcast Approaches

Deterministic broadcast approaches typically use topology information and are based on imposed decision. Thus, the sender of a broadcast message specifies in the message which neighbors have to perform a rebroadcast. In contrast to simple flooding, deterministic approaches explicitly select a small subset of neighbors as forwarding nodes which are sufficient to reach the same destinations as all nodes together. Therefore, a relaying node has to know at least its one-hop neighbors.

These type of protocols were some of the first suggested by the research community to minimize the broadcast overhead in order to overcome the broadcast storm problem. Characteristically, these protocols achieve a very high efficiency, because based mostly on two-hop neighborhood information, very accurate rebroadcast decisions can be calculated. Therefore, many variants of deterministic broadcast protocols can be found in the literature. Examples are dominant pruning [189], multipoint relaying (MPR) [190], total dominant pruning [203], and many cluster-based approaches (see e.g. [204] and [205]). These approaches are discussed in the following.

#### Preliminaries

The goal of deterministic broadcast is to build a broadcast tree of so called forwarders or relay nodes responsible for distributing the message to all nodes in the network, respectively to the nodes inside the target geographic region. These relay nodes form a Connected Dominating Set (CDS) which is a virtual backbone and ensures a full coverage [206]. A CDS with minimal size is called Minimum Connected Dominating Set (MCDS) and it represents the optimum in terms of communication efficiency, thus the goal of such approaches is to find a possibly small CDS. Unfortunately, finding an optimal subset (i.e. with minimal size) is NP-complete [207, 190]. Therefore, heuristics are used to find not necessarily optimal but still sufficient relaying nodes [208, 209, 210, 211, 206, 212, 213].

In the following, a more formal definition of the deterministic broadcast problem is given. This notation is then used in the subsequent sections for the evaluation of different broadcast approaches. Given an undirected graph $G = (V, E)$, where $V$ is a set of vertices (nodes) and $E$ the set of communication links between the nodes in the network.

**Definition 1.** *The open neighbor set $N(v)$ of node $v$ is defined as:*

$$N(v) := \{w : (w, u) \in E\}$$

.

Thus, the open neighbor set of node $v$ contains all adjacent nodes inside its communication radius. Whereas the closed neighbor set contains the node itself too:

**Definition 2.** *The closed neighbor set $N[v]$ of node $v$ is defined as:*

$$N[v] := N(v) \cup \{v\}$$

.

Furthermore, $N(N(v))$ represents the set with all one-hop and two-hop neighbors of node $v$, together with node $v$ itself. Based on this, the set of two-hop neighbors can be defined:

**Definition 3.** *The set of two-hop neighbors $N^2$ of node $v$ is defined as:*

$$N^2(v) := N(N(v)) \setminus N(v) \setminus \{v\}$$

For building a virtual broadcast backbone, the notion of CDSs is important. A CDS is a special case of a Dominating Set (DS), both are defined as follows.

**Definition 4.** *A subset $V' \in V$ is a Dominating Set (DS) of $G$ ($DS(G)$) if*

$$V' = DS(G) :\Longleftrightarrow \forall v (v \in V \setminus V' \rightarrow \exists u \in V' : v \in N(u))$$

Thus, all nodes have to be either member of the DS or have a neighbor in the DS. Such a DS is not enough to reach all nodes in the network, because the forwarding nodes are not necessarily connected. Therefore, a CDS is needed which is defined as follows.

**Definition 5.** *A Connected Dominating Set (CDS) of $G$ is a DS of $G$ such as it induces a connected subgraph.*

Based on this notation, we are reviewing several broadcast protocols proposed in the literature. All of them have the same goal: to build a possibly minimal CDS. Therefore, several approximation algorithms were proposed, based on different heuristics, which are discussed in detail in the following.

### Wu and Li's algorithm

The algorithm proposed by Wu and Li in [214] is based on two-hop neighborhood information. It uses a marking process to establish a set of gateway nodes forming a Connected Dominating Set (CDS). In a first step, a node $v$ will be marked as gateway, if it has two neighbors which are directly connected. Because this initial CDS is far from optimal, two heuristics based on pruning were proposed by the authors to minimize it. Let $N[v] = N(v) \cup \{v\}$ be the closed neighbor set of node $v$ and $P(v)$ the priority of node $v$. These two optimization heuristics are defined as follows:

- *Rule 1:* Assume two nodes $v$ and $u$ which are marked as gateways. If

  $$N[v] \subseteq N[u] \wedge P(v) < P(u)$$

  then node $v$ can be unmarked, thus it will become a nongateway.

- *Rule 2:* Assume the two marked nodes $u$ and $w$ are neighbors of node $v$. If

$$N(v) \subseteq N(u) \cup N(w) \wedge P(v) = min\{P(v), P(u), P(w)\}$$

  then node $v$ can be unmarked.

For the determination of a node's priority the authors propose two alternatives: simply using the node id or a combination of a node's degree and node id.

The authors also note that rule 2 can be easily generalized in a way to check the coverage of a node's open neighbor set by more than two adjacent marked nodes. This extended rule is called *Rule k* and is described in [215].

### Scalable Broadcast Algorithm

The Scalable Broadcast Algorithm (SBA) introduced by Peng and Lu in [180] uses two-hop neighbor knowledge and a deferred retransmission for the retransmission decision process. The SBA algorithm is based on the following idea: Suppose node $u$ sends a broadcast message which is received – among other nodes – by its direct neighbor $v$. Based on two-hop neighbor knowledge, $v$ can determine which nodes – that are the direct neighbors of $u$ – have already received that message. If it has no additional neighbors compared to those of node $u$ then a rebroadcast will not be needed. Else this node sets a random timer, this time interval is called Random Assessment Delay (RAD). During this time rebroadcasts from other nodes are overheard. Based on such overheard rebroadcasts, node $v$ actualizes the set of received nodes and determines if it can still reach new neighbors. If not, then the rebroadcast will be canceled. After the set time, a rebroadcast can reach new nodes, thus the retransmission of the message is performed.

In the following the protocol executed by node $v$ upon reception of a broadcast message from its neighbor $u$ is described more precisely:

1. Let $R = N[u]$ be the set of nodes which already received the message.
2. If $N(v) \subseteq R$ then no progress can be made by a rebroadcast, thus it can be canceled. Else set the RAD timer and overhear subsequent rebroadcasts of that message.
3. Wait until the timer has finished. Then go to step 6.
4. Upon overhearing of the broadcast message from node $w$ update the set of received nodes: $R = R \cup N[w]$.
5. If $N(v) \subseteq R$, cancel the broadcast. Else go to step 3.

6. Perform the rebroadcast of the message.

It is obvious that setting a shorter RAD for nodes which can reach more nodes by a rebroadcast as others is more efficient. For this reason, the authors proposed such a dynamic selection of the delay interval. In that scheme, the delay is based on a node's number of neighbors, called neighbor degree and denoted as $d(v)$. Therefore, a node $v$ searches its neighbor table for the node with the maximum neighbor degree $d_{max}(v)$. The delay is then based on the quotient of that maximum and the own neighbor degree. For a node $v$ the delay time $T$ is calculated based on the following equations:

$$T0 = (1 + d_{max}(v))/(1 + d(v))$$

$$T = U(\Delta \times T0)$$

where $\Delta$ is a constant delay and $U(x)$ is a function returning a uniformly distributed random number between 0 and $x$.

The authors showed by simulations that SBA efficiently reduces the number of rebroadcast messages compared to flooding. As shown in these results, up to 60% of redundant messages can be saved by applying SBA. On the other hand, the disadvantage of this scheme is the use of two-hop neighborhood information. For that local topology knowledge, additional beacon messages with neighbor tables have to be exchanged periodically. Additionally, such neighbor tables may become outdated due to node mobility. Thus, in highly dynamic environments no accurate rebroadcast decisions can be made anymore, leading to a degradation of the delivery ratio of the broadcast protocol.

### Self pruning

Self pruning [189] is a topology-based protocol using only one-hop neighbor knowledge. Therefore, each node periodically exchanges so called hello messages by using a beaconing mechanism. The idea is to rebroadcast a message only if that rebroadcast would reach additional nodes compared to the previous transmission. Therefore, an initiator of a broadcast message piggybacks the own neighbor table into that message. When an adjacent node is receiving that transmitted message, it compares the transmitted neighbor list to its own neighbor table. Thus, it can be determined whether a rebroadcast of the message would reach new nodes or not.

Thus, the forwarding decision is based on the difference of these two sets. Assuming node's $u$ closed neighbor table is $N[u]$ and this table is sent with the broadcast message to its neighbor $v$, then node $v$ makes the rebroadcast decision based on its own neighbor set minus the received neighbor set: $N(v) \setminus N[u]$. If this set is empty, then no new nodes can be reached, thus the node $v$ will not forward the message. If the calculated set is not empty, the message is rebroadcast.

Self pruning represents a very simple mechanism to make information dissemination more efficient. It reduces the communication overhead compared to flooding as was shown by simulations in [189]. The advantage of the protocol is that it relays only one one-hop neighbor knowledge which requires much less communication overhead compared to two-hop neighbor tables. The disadvantage of the protocol is that it piggybacks the neighbor table into the broadcast message, thus increasing the size of the broadcast messages. Furthermore, because only one-hop neighbor knowledge is used, the rebroadcast decision is far from optimal, this protocol performs much worse than broadcast protocols based on two-hop neighbor knowledge (see e.g. a comparison to dominant pruning presented in [189]).

#### Dominant pruning

Besides self pruning, Lim and Kim proposed in [189] a second broadcast approach, known as dominant pruning. In contrast to self pruning, dominant pruning uses two-hop topology information for the rebroadcast decision. Moreover, it applies an imposed-decision-based scheme, the determination of relay nodes by the sender. This information is piggybacked with the broadcast message in order to inform relay nodes.

For the determination of the set of relaying nodes, dominant pruning uses a greedy set cover algorithm [203]. The idea of this algorithm is that a node selects first those one-hop neighbors adjacent to the most two-hop neighbors of this node. I.e. first these neighbors are selected which can rebroadcast the message to the most two-hop neighbors, thus this way nodes with a huge additional coverage area are favored. This selection is repeated until all two-hop neighbors are covered. This process is described in the following more precisely according to [189].

Let $N(v)$ be the adjacent node set of node $v$ then the set of two-hop neighbors is $N^2(v) = N(N(v))\setminus N(v)\setminus\{v\}$. If node $v$ has to forward a message upon reception from node $u$, it first determines the set of two-hop neighbors for which it is responsible to forward that message: $U = N^2(v)\setminus N(u)$. The neighbors of $u$ already received the message, thus they are subtracted from the two-hop neighbors of $v$. The potential relays are the adjacent nodes of $v$ which are not direct neighbors of $u$ (else they were already considered as forwarders by $u$) and are defined as $B(u,v) = N(v) \setminus N(u)$. Then the set of forwarders $F = \{f_1, f_2, , f_m\} \subseteq B(u,v)$ needs to be selected so that all two-hop neighbors are covered: $\bigcup_{f_i \in F}(N(f_i) \cap U) = U$. For a clarification, see these sets depicted in Figure 4.2.

The goal is to find a small set of forwarders and thus to minimize the communication overhead. Therefore, a *greedy set cover* algorithm from [216] is used. In the following this

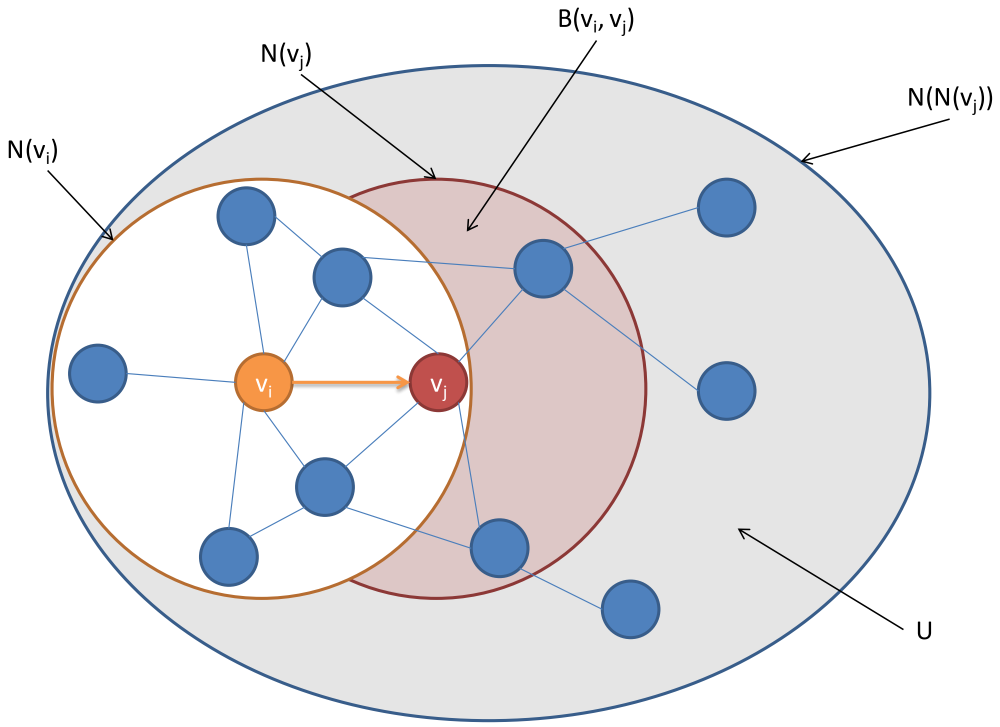


Figure 4.2: Dominant pruning based on neighbor knowledge [189].

algorithm is detailed:

1. Let $F = \emptyset$, $K = \{S_1, S_2, , S_n\}$ where $S_k = N(v_k) \cap U(1 \leq k \leq n)$, $Z = \emptyset$.
2. Find the set $S_k$ in $K$ whose size is maximal.
3. $F = F \cup \{v_k\}, Z = Z \cup S_k$, $K = K \setminus \{S_k\}$, $S_l = S_l \setminus S_k$ for all $S_l \in K$.
4. If all two-hop neighbors are covered – that is $Z = U$ – then finished.
5. Otherwise, repeat from 2 again.

Based on this algorithm, dominant pruning achieves very efficient rebroadcast decisions, thus the communication overhead of such broadcast methods are minimal. This significant performance gain compared to simple flooding was shown by simulations in [189].

### Multipoint Relaying

A very similar approach to dominant pruning is Multipoint Relaying (MPR), proposed by Qayyum et al. in [217, 122, 190]. MPR uses also two-hop topology information and a similar greedy algorithm for the CDS determination. The major difference between dominant pruning and MPR is that dominant pruning piggybacks the calculated relay nodes with the broadcast message whereas MPR distributes the relay set of a node via beacon messages.

Another difference to dominant pruning is an extended initialization step of the greedy set algorithm to optimize the relay set. In that extension, the set $F$ is initialized with these one-hop neighbors, which are the single connection to some two-hop neighbor nodes. Such one-hop neighbors need to be added anyway – and are added by the original algorithm – but it is better to include them at the beginning and thus reducing the remaining set of two-hop neighbors before the iterative steps greedily eliminate them.

In [206] several extensions to MPR are presented which enable the determination of an even smaller CDS as relays. Unfortunately, they are based on three-hop neighbor knowledge which is too expensive – in terms of communication overhead – to maintain in highly dynamic environments like VANETs.

Although efficiency is one of the most desirable properties of broadcast protocols, dominant pruning and MPR have several serious disadvantages which are outlined in the following.

- *Two-hop neighbor knowledge*: The forwarding decision is based on two-hop neighbor information which have to be exchanged periodically in beacon messages. This increases the communication overhead and therefore, this property is unfavorable compared to approaches which require only one-hop neighbor information. Moreover, due to node mobility as is the case in VANETs, such neighbor tables become outdated. This may lead to wrong rebroadcast decisions.

- *Lack of robustness*: Minimizing the set of forwarding nodes represents a disadvantage in the perspective of robustness. This behavior was already observed by the authors in [190]. If for example a relay node fails to rebroadcast a message, then it can lead to drastically decreased reception rates, that is the failure of a broadcast protocol. Imagine for example a highway scenario where based on the road topology only a minimal set of nodes have to rebroadcast a message in order to flood the message to all nodes in a road segment. If one such relay fails at the beginning of the broadcast process, the probability that the majority of the nodes will not receive a message is high. In VANETs there are many reasons why such relay nodes can fail to rebroadcast a message: especially the error prone wireless communication and the high network dynamicity cause such approaches to degrade drastically, as we are going to show by simulations in our evaluation.

- *Imposed-decision-based*: The imposed decision means that the message relays are selected in advance by the last hop. This implies the knowledge of topology information which may be outdated. For example, node $v$ selects its neighbor $u$ as relay and sends the message. If in the meantime node $u$ moved out of the communication range of node $v$, then that message would get lost. Thus, such imposed-decision-based approaches are also affected by node mobility. Because of these properties, imposed decision is a possible cause for lack of robustness.

Although these two approaches were not originally designed for VANETs, they reveal important properties. Also in such highly dynamic environments they can provide some significant advantages. Therefore, we are going to merge these properties with those probabilistic approaches as discussed in Section 4.3.3.

### Ad-hoc Broadcast Protocol

The Ad-hoc Broadcast Protocol (AHBP) [218] is a very similar approach to MPR with some additional optimizations. These extensions are detailed in the following:

1. For being as accurate as possible, the relay nodes are determined during the rebroadcast process and the relay set is piggybacked into the broadcast message (as is the case of dominant pruning). In contrast to that, MPR periodically distributes a node's relays through beaconing.

2. Before determining the relays, AHBP reduces the set of two-hop neighbors by removing the nodes which have already received the message. Therefore, the local two-hop neighbor knowledge is used, and additionally the path of the broadcast message is recorded into the message header. This way the number of relays can be further reduced compared to MPR leading to a more efficient protocol.
3. The authors propose another extension to cope with high node mobility. Due to such high mobility, neighbor tables get outdated, e.g. there could be adjacent nodes which moved inside communication range but have not yet exchange beacon messages. Thus, they are not listed in the neighbor table. Therefore, when a node $v$ receives a message from $u$ and $u$ is not in the node's neighbor table, it rebroadcasts the message even if it was not marked as relay in that message.

As shown by simulations in [219], these optimizations enhance the efficiency compared with MPR.

#### Stojmenovic's algorithm

Stojmenovic et al. suggest in [220] three optimizations for Wu and Li's algorithm [214]. First, they propose the use of position information, thus the marking process can be realized based on only one-hop neighbor knowledge. Second, the CDS is further optimized by unmarking a node if all its neighbors were covered from other marked nodes which already rebroadcast that message. Therefore, a random backoff counter is set to overhear subsequent rebroadcasts from other nodes. When the timer expires, the node checks if it can still cover additional nodes and if not, it un-marks itself. Third, the Retransmission After Negative Acknowledgements (RANA) protocol is proposed to enhance reliability. The authors assume that the first two slots are enough to retrieve the identifier and the sender of the message. Thus, when a collision occurs after slot two, then a node explicitly could request a rebroadcast of a message.

By using position information, the protocol significantly reduces the communication overhead for the marking process. This is a significant and essential advantage compared to the primary approach. The second optimization lowers the CDS at the expense of the additional delay.

#### Lou and Wu's algorithm

Lou and Wu propose in [203] two extensions to the dominant pruning algorithm [189]: Total Dominant Pruning (TDP) and Partial Dominant Pruning (PDP). Both extension intend to optimize the CDS and are explained in the following.

In TDP a node $u$ which broadcasts a message to its neighbor $v$ piggybacks its two-hop topology information $N(N(u))$ into the broadcast message. Using this information, node $v$ can reduce the set of two-hop neighbors which have to be covered. More specifically, node $v$ eliminates also the two-hop neighbors of $u$ from its own two-hop neighbors to cover: $U = N(N(v)) \setminus N(N(u))$. Based on this reduced set, the dominant pruning algorithm is performed as previously described in [189].

In the PDP algorithm no topology information is piggybacked with the broadcast message. Therefore, at node $v$ no two-hop neighbor topology of node $u$ is available. Thus, $N(N(u))$ cannot be subtracted from $N(Nv))$ as in the TDP. But the idea is to determine two-hop neighbors of $u$ based on node's $v$ two-hop topology information. It means the determination of all neighbors of the common one-hop neighbors of $u$ and $v$: $P = N(N(u) \cap N(v))$. These nodes can be removed from the set which has to be covered by $v$: $U = N(N(v)) \setminus N(u) \setminus N(v) \setminus P$.

Based on additional knowledge, TDP achieves a better reduction of the CDS. This improvement is at the cost of the increased broadcast message size which piggybacks the two-hop topology data of the last sender. The PDP enhancement does not require such information to be piggybacked but uses only the local two-hop neighbor information of the rebroadcast nodes. However, as the authors show by simulations, the difference – in terms of broadcast redundancy – between these two enhancements is insignificant. On the other hand, dominant pruning is outperformed by both approaches.

#### Briesemeister and Hommel's protocol

In [221], Briesemeister and Hommel propose the introduction of a retransmission delay which is inversely proportional to the distance between a relay node and the previous sender of that message. The rationale behind this deferred rebroadcast is the following: a link layer broadcast is potentially received by several nodes simultaneously. These nodes perform the same routing protocol, thus they would perform a rebroadcast at the same time. These immediate rebroadcasts lead to burst traffic which resulting in packet loss due to collision.

To overcome this problem, the authors propose the following function to calculate the wait time ($WT$) based on the distance $d$:

$$WT(d) = -\frac{MaxWT}{Range} \cdot \hat{d} + MaxWT$$

where $Range$ is the transmission range and $maxWT$ the maximum wait time. The applicability of this protocol was shown by simulations. A very similar approach can be found in [222].

#### The TRAck DEtection and Distance Defer Transmission Protocols

In [223] Sun et al. introduce two broadcast protocols designed for VANETs. The first is called Track Detection (TRADE) and is based on the idea that on streets only the most distant nodes have to rebroadcast a message. For the selection of these relays, TRADE periodically exchanges geographic position information of vehicles in beacon messages. Each node categorizes its neighbors based on their position collected over time into three categories: *same road ahead*, *same road behind*, and *different road*. From the first two categories the most distant nodes are selected as relay nodes, whereas from the third set all nodes are regarded as relays. The IDs of these relay nodes are transmitted together with the broadcast message.

The drawback of the TRADE protocol is the communication overhead needed for the exchange of geographic position information. Therefore, the authors propose a second protocol trying to determine the most distant nodes based on a delay period which is inverse proportional to the distance between the source and the receiver of a broadcast message. Therefore, this so called Distance Defer Transmission (DDT) protocol does not use beaconing at all. A sender of a broadcast message piggybacks its geographical position into the broadcast message. Upon reception, a node calculates its distance to the source node based on this information. Based on that distance the defer time is calculated which is inversely proportional to it. Thus, a more distant node rebroadcasts a message faster. During this defer period, a node overhears the channel for other rebroadcasts of that message. Based on the position information of that relay node, it calculates additional coverage of a rebroadcast. If it is above a certain threshold, the node will rebroadcast the message after the end of the defer period.

Besides the additional overhead introduced by the period exchange of position information, the main drawback of the TRADE protocol is twofold. First, the relays from the sets *same road behind* and *different road* represent a single point of failure. If they fail to rebroadcast a message, then the reception rate could drop drastically. Because the selection of the most distant nodes, this is highly possible: The error rate at the border of the transmission range is much higher as at shorter distances and there is a higher probability, that such a relay node is no longer in transmission range due to node mobility. Second, it is not clear how exactly relays from the third set should be selected. If all nodes are selected, then in some situations the efficiency could drop significantly. The drawback of the second approach is the delay introduced by the deferred rebroadcast and the determination of an accurate additional coverage area threshold used for the rebroadcast decision. It is obvious, that a fixed value is not practicable in dynamic networks like VANETs.

### The Urban Multi-Hop Broadcast Protocol

Korkmaz et al. propose in [45] the *Urban Multi-Hop Broadcast (UMB)* protocol. The objective of that protocol is to rule out the shortcomings of IEEE 802.11 broadcast-based protocols: the lack of a Request-to-Send/Clear-to-Send (RTS/CTS) scheme to overcome the hidden terminal problem. The idea of that protocol is that vehicle movement is constrained by the streets, thus a message is typically disseminated in one direction linearly. Therefore, it will be enough if the most distant vehicle responds with a clear-to-send to a request-to-send message. If that vehicle forwards the message, then also the dissemination progress will be maximized. This mechanism is called *Request-to-Broadcast/Clear-to-Broadcast (RTB/CTB)* and is detailed in the following.

Before transmitting a broadcast message, vehicle $v$ divides its covered area in a given number of segments. Then it sends a *Request-to-Broadcast (RTB)* message using a link layer broadcast. This message contains the geographical position of $v$ and the number of segments. Upon receiving this message, a node $u$ transmits a so called *black-burst* jamming-signal. The length of that *black-burst* is computed as follows:

$$L = \lfloor \frac{\hat{d}}{Range} * N_{max} \rfloor * SlotTime$$

where $\hat{d}$ is the distance between node $v$ and $u$, $Range$ is the maximum transmission range, $N_{max}$ is the number of segments assigned by $v$, and $SlotTime$ is the length of one slot. Thus, the *black-burst* length is proportional to $\hat{d}$. The farer away node $u$ is from $v$, the longer it jams the channel. When $u$ terminated the *black-burst*, it overhears the channel: If another node is jamming, then that node is farer away from $v$, thus $u$ must not relay the message. It can cancel the rebroadcast process. Otherwise it sends the *Clear-to-Broadcast (CTB)* to signal $u$ to start the message transmission. If more than one node is located in one segment – i.e. they will send the CTB at the same time – then node $v$ refines the number of segments and starts the RTB/CTB process again. This way the protocol dynamically adapts to the different network densities.

The RTB/CTB scheme selects the node in the furthest segment as a relay of the broadcast message. The disadvantage of this scheme is, that it introduces a significant latency, especially in dense networks.

### The Smart Broadcast Protocol

In [224] an improvement of the previously discussed UMB protocol was introduced. This new broadcast protocol is known as Smart Broadcast (SB). One of the drawbacks of the UMB protocol is that relay nodes are assigned the longest black-burst duration, hence the rebroadcast delay increases significantly. The SB protocol overcomes this problem by assigning relay nodes the shortest delay. SB uses the RTB/CTB from the UMB protocol but without the black-burst. Instead, it uses a randomly chosen backoff timer which is based on the distance to the sender of the RTB message. Nodes on the border of the transmission range are assigned lower values as nodes which are near the source node.

Because the SB scheme minimizes the rebroadcast latency, it has no mechanism to overcome possible collisions. To increase the robustness, the authors propose a backoff counter also for the sender of the RTB message. If this backoff is cleared and no valid CTB message was received, then the node will start the broadcast procedure again.

### Intelligent Broadcast with Implicit Acknowledgement

Another broadcast scheme is introduced in [225] by Biswas et al. using implicit acknowledgements. In this Intelligent Broadcast with Implicit Acknowledgement (I-BIA) protocol a source starts the dissemination process by periodically performing a link layer broadcast of the message which needs to be disseminated. This periodic rebroadcast lasts until that node received the message from behind. I.e. that message was relayed by at least one vehicle into the dissemination direction. Upon reception of such a broadcast message, a node sets a randomly chosen backoff timer and overhears the wireless medium. If this node receives a rebroadcast from another node, then its rebroadcast process can be stopped. Else it starts the periodical rebroadcast the same way as the source node did, until an implicit acknowledgement is received.

This implicit acknowledgement increases the robustness of the dissemination protocol. But it is not clear how the protocol performs in other but highway scenarios. It seems that this rigid linear assumption has severe drawbacks on intersections, curvy roads and other non linear scenarios. Another question is when to stop the periodic rebroadcast if no implicit acknowledgement was received.

### Parameterless Broadcasting from Static to Mobile Networks

Another interesting approach is the Parameterless Broadcasting from Static to Mobile (PBSM) protocol proposed by Khan et al. in [226]. It uses a novel delayed rebroadcast approach which is based on a CDS to prioritize backbone nodes. This CDS is computed using two-hop neighbor information exchanged by beacons.

This information is also used to compute two sets for each broadcast message: $R$ the set of one- and two-hop neighbors which received the message and the set of nodes ($N$) which still need to receive the message. The size of $N$ also affects the rebroadcast delay: the delay is inversely proportional to the size of this set. If this set is cleared up then no rebroadcast will be needed.

This set is also used to overcome network partitions. If a node received a beacon message from an unknown node, this node is inserted into the set $N$. Thus, the node starts its backoff timer and rebroadcasts the message if that node was not covered by other rebroadcasts during the delay period.

In [227] two extensions of the PBSM are proposed: 1) explicit acknowledgements of broadcast messages and 2) the use of only one-hop neighbor information. For the first enhancement the Acknowledged PBSM (AckPBSM) protocol piggybacks the identifiers of recently received broadcast messages into the beacons. When a node relays a broadcast message, it sets a timeout with a duration larger than the beaconing interval. After expiration, it checks if every neighbor acknowledged the reception. If a neighbor has not received the message – i.e. the message identifier was not incorporated into the beacon – the neighbor is moved from $R$ to $N$. If a neighbor has not sent a beacon at all, then it is removed from the set $R$. The second enhancement is the use of only one-hop topology information to build the CDS. Therefore, the algorithm from [220] is used. For more details see also [228].

### Position-based Adaptive Broadcast

Another delayed retransmission broadcast approach is introduced by Yang and Chou in [229]. Compared to other delayed broadcast approaches, this so called Position-based Adaptive Broadcast (PAB) protocol uses also velocity and heading information besides position information of the sender and receiver. Hence the calculated delay time not only prioritizes distant relying vehicles, but also those travelling in the dissemination direction with higher velocities. To determine these information, in each broadcast message the following information is added: 1) the current position of the sender, 2) the previous position of the sender, and 3) the position of the originator of the broadcast message.

Considering these additional information for the calculation of the delay period, a more accurate delay time can be calculated. This allows a more efficient directed dissemination of warning messages. According to our classification, such a delayed rebroadcast represents an orthogonal improvement. The combination also with other dissemination protocols is possible.

### Distributed Robust Geocast

In [230] Kihl et al. introduce a new GeoCast protocol for VANETs based on a deferred retransmission, similar to the UMB protocol of [45]. The novelty of this DRG protocol is

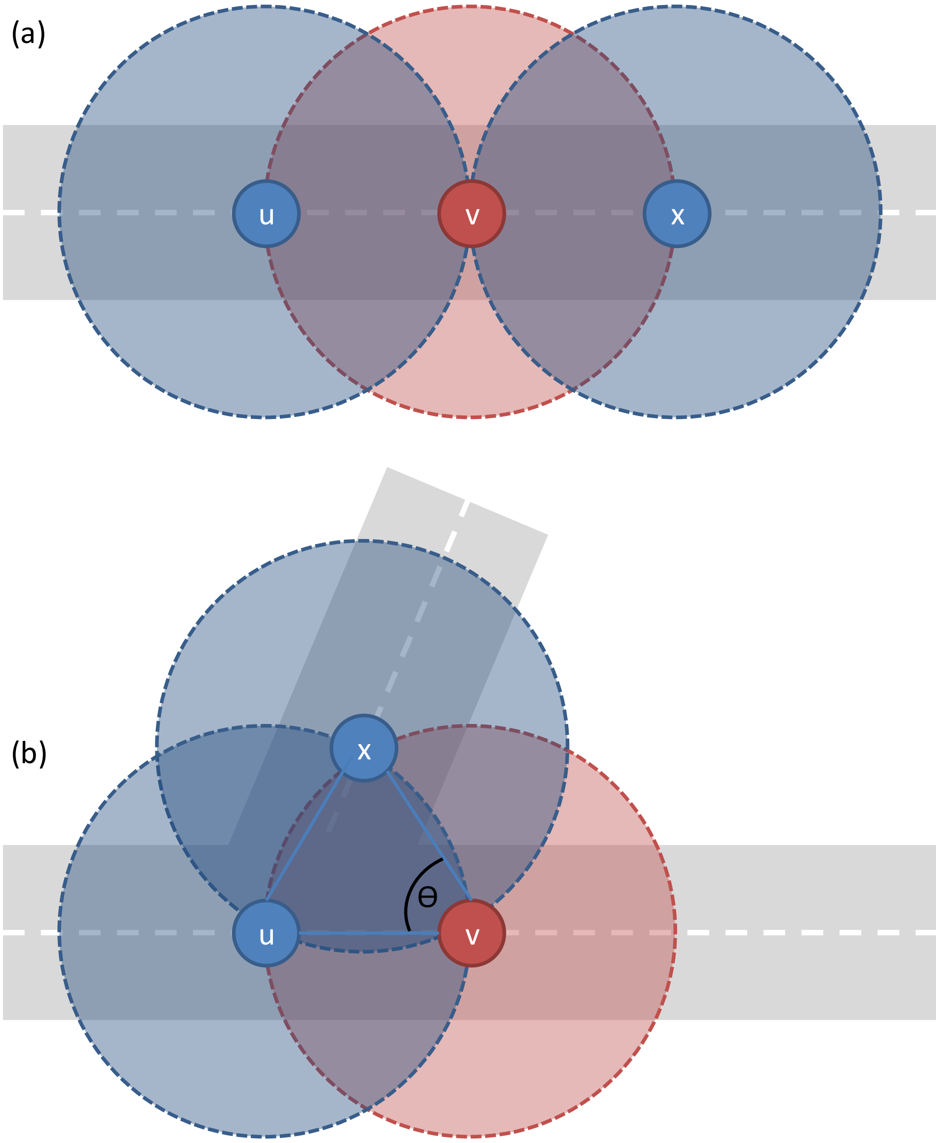


Figure 4.3: Two example scenarios for the DRG protocol.

first, the enhancement for a two-dimensional dissemination – in contrast to UMB designed for linear scenarios like highways – and second, the introduction of a short and a long delayed retransmission to enhance robustness.

The DRG protocol uses a backoff timer function similar to that of UMB. Using this delay function, nodes which are more distant from the previous sender are more likely to become a relay. The first enhancement is the consideration of two-dimensional dissemination. Consider e.g. an example where node $u$ is the initiator of a broadcast message which was received by node $v$ as depicted in Figure 4.3. After the rebroadcast, node $v$ overhears the channel for other rebroadcasts. Upon acknowledgement by node $x$ performing a rebroadcast, node $v$ has to evaluate the possibility of reaching additional nodes by performing a rebroadcast. In the first scenario (Figure 4.3 (a)), the rebroadcast by $v$ would be redundant, because the dissemination direction would be the same as the rebroadcast of node $x$. I.e., the message would be disseminated on the same road, where nodes already received the broadcast from node $x$. On the other hand, in scenario (b) a rebroadcast should be performed, because node $x$ disseminated the message into another direction on another road. There is a high probability to reach new nodes by a rebroadcast of the message through $v$. Therefore, the authors propose the use of a threshold for the rebroadcast decision based on the depicted angel $\theta$.

The second enhancement is the introduction of both, a short delayed and a long delayed retransmission. The short delayed retransmission is used as countermeasure to packet losses, whereas the long delayed retransmission is applied to overcome network partitions. For details see [230].

### The TLO Broadcast Protocol

In [231], a broadcast protocol known as The Last One (TLO) is proposed. The objective is to reduce the number of rebroadcasts by selecting the most distant node from the previous broadcast in dissemination direction. Therefore, the authors assume a highway scenario where the message is disseminated into one direction. Vehicles use beacon messages to periodically exchange their geographical position information. On reception of a broadcast message, a node $v$ determines its distance to the last hop. Additionally, the distance is calculated for all neighbors which also received the message. This distances are compared and the last node is determined. If $v$ is the last hop, it will rebroadcast the message. Otherwise it starts a timer and overhears the channel for rebroadcasts from neighbor nodes. If no rebroadcast of that message takes place after the timeout, the rebroadcast procedure will start again.

Unfortunately, this protocol assumes a linear dissemination of messages on a highway, thus it cannot be applied generally. Also it is not clear, how inaccuracy of sender positions are handled, because this could lead to a degradation of the dissemination performance, as also stated by the authors. Moreover, for the determination of the TLO node the theoretical transmission range and the neighbor positions exchanged through beacons are used. This introduces additional inaccuracy which has a negative effect onto the dissemination's performance.

### The REAR Protocol

As we have seen, there are many contention-based approaches for VANETs. Mostly they use the distance between the last hop and the receiver of a message to prioritize more distant nodes in order to maximize dissemination progress.

Another contention-based approach is the Receipt Estimation Alarm Routing (REAR) protocol from [232] which uses a completely different approach to determine the backoff timer. The authors argue that farther nodes – which are preferred by distance-based methods – may have low receipt probabilities. This could lead to failures in the relaying process. Therefore, the authors propose to use the estimated receipt probability of nodes to calculate the delay. A node whose neighbors have high receipt probabilities should be preferred, because they allow a more reliable dissemination. The receipt probability of neighbors is calculated based on their signal strength, position and size of vehicles.

The authors show the advantage of REAR over distance-based contention protocols by means of simulations. This evaluation shows that REAR outperforms the other protocols in terms of reliability and efficiency. On the other hand, it reveals the main disadvantage of REAR: the dissemination delay is much higher compared to other approaches. This is due to the fact, that in REAR not the nodes allowing a larger progress are preferred, but nodes which are more likely to successfully relay the message to their neighbors.

### The LDMB Protocol

A second approach which uses the link-quality as a metric for the backoff delay determination is presented in [233]. In this Link-based Distributed Multi-hop Broadcast (LDMB) protocol a node calculates its backoff delay based on its distance to the last hop, transmission power, transmission rate, and vehicular density. As shown by simulations, the LDMB protocol achieves nearly the same reception rates as the purely distance-based approaches, but achieving shorter packet delivery times.

### The DECA Protocol

Nakorn and Rojviboonchai propose in [234] a reliable broadcast protocol which selects relay nodes according to their connectivity. This protocol is called Density-Aware Reliable Broadcast (DECA). Beaconing is used to exchange a node's density information with its neighbors. When a node rebroadcasts a message, it selects its neighbor with the highest connectivity as the next relay by inserting this neighbor's identifier into the broadcast message. Upon reception, these nodes immediately rebroadcast the message using the same process for selecting the next relay. Other neighbors store the received message and overhear the wireless medium for a randomly chosen period of delay time for implicit acknowledgements. If a node did not receive such an acknowledgement, it would perform the rebroadcast itself using the same algorithm.

The authors propose also a mechanism similar to AckPBSM from [227] to overcome partitioned networks. Therefore, the identifiers from recently received broadcast messages are transmitted with the beacon messages. If a node comes into communication range with another node, the beacon received reveals if that node is missing a broadcast message. In this case the node performs a rebroadcast of that message. Here the selected relay field is left blank.

The drawback of the DECA protocol is that it was designed for the dissemination into one direction. I.e. the performance of the protocol is only good in highway scenarios, where messages are disseminated directed.

### Discussion

As we have seen, there do exist a large range of deterministic broadcast approaches. Most of them were designed for MANETs but there are also many approaches exclusively designed for VANETs. Summarizing their characteristics as shown in Table 4.1, two main protocol types can be distinguished:

- *Delayed rebroadcast-based approaches*: Before retransmitting a message, a node waits a certain time period to optimize its rebroadcast decision based on overheard messages.
- *CDS-based approaches*: A rebroadcast decision is based on some heuristic trying to minimize the CDS. A relay node rebroadcasts a message without the introduction of some additional delay.

| **Protocol** | **Type** | **Decision** | **Inf. Type** | **Delay Function** | **Beacon Data** | **Message Data** |
|---|---|---|---|---|---|---|
| Wu and Li's algorithm | CDS | local | topology | - | two-hop topology | - |
| SBA | delayed | local | topology | neighbor degree | two-hop topology | - |
| Self Pruning | CDS | local | topology | - | one-hop topology | one-hop topology |
| Dominant Pruning | CDS | imposed | topology | - | two-hop topology | relay set |
| MPR | CDS | imposed | topology | - | two-hop topology | - |
| AHBP | CDS | imposed | topology, message path | - | two-hop topology | relay set, message path |
| Stojmenovic's algorithm | CDS and delayed | local | topology, position | random | one-hop topology | - |
| TDP | CDS | imposed | topology | - | two-hop topology | two-hop topology, relay set |
| PDP | CDS | imposed | topology | - | two-hop topology | relay set |
| Briesemeister and Hommel's protocol | delayed | local | position | distance | - | sender position |
| TRADE | CDS | imposed | position | - | node's position | relay set |
| DDT | delayed | local | position | distance | - | sender position |
| UMB | delayed | local | position | distance | - | - |
| SB | delayed | local | position | distance | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| I-BIA | delayed, periodic rebroad-cast | local | position | random | - | sender position |
| PBSM | delayed | local | topology | CDS | two-hop topology | - |
| AckPBSM | delayed | local | topology, position | - | one-hop topology | - |
| PAB | delayed | local | position, heading and velocity | distance, heading and velocity | - | current and previous position of sender, initiator position |
| DRG | delayed | local | position | distance | - | sender position |
| TLO | CDS | local | position | - | position | sender position |
| REAR | delayed | local | topology, position, vehicles' size, dissemi-nation direction | reception probability | location, vehicles' size | message propaga-tion direction and the sender neighbor list |
| LDMB | delayed | local | position | link quality | position | - |
| DECA | CDS | imposed | topology, density | - | density | relay |

Table 4.1: Summary of deterministic broadcast protocols.

The delayed rebroadcast-based approaches also try to approximate CDS of minimal size, but these approaches introduce a delay to enhance the CDS determination by information received from other overheard messages. As already discussed in Section 4.2, delayed rebroadcast represents an orthogonal enhancement. I.e., such schemes are not restricted to deterministic approaches, but they can be applied also for probabilistic broadcast approaches. We discussed these approaches for their significance in the context of vehicular information dissemination but we do not further investigate these schemes in this work. We argue, that they should be considered to be integrated as a cross layer approach into the Media Access Control (MAC) layer.

The second type of broadcast schemes build a CDS based on information gathered from beacon messages and from information piggybacked with the broadcast message. For the determination of the rebroadcast decision typically topology information is used – especially in the case of protocols designed for MANETs – whereas approaches proposed for VANETs mostly utilize position information. Using such geographical position information from one-hop neighbors, equivalent CDSs can be determined compared to approaches which use solely two-hop topology information. Despite the fact that for VANET applications the presence of a beaconing service is a prerequisite, it is highly desirable to exchange only one-hop neighbor information in order to keep the size of the beacon messages minimal.

Despite the high efficiency, deterministic broadcast has a significant disadvantage: relaying nodes represent a single point of failure. If a relay fails to forward a message (e.g. due to wireless losses, node failure, or not being in transmission range due to mobility) then the overall reception rate of the message might drop significantly. Thus, these kind of protocols lack robustness and perform poorly in dynamic environments like VANETs. Therefore, they cannot be used for safety critical applications in VANETs and more robust – but at the same time also efficient – broadcast schemes are needed.

### 4.3.2 Probabilistic Broadcast Approaches

Whereas deterministic broadcast approaches use a possibly minimal CDS for the determination of forwarding nodes, probabilistic approaches' forwarding decision is based on a probabilistic function. I.e. on reception of a broadcast message, a node rebroadcasts that message with a certain probability. In this section such broadcast approaches proposed for MANETs are discussed.

### Ni's Probabilistic Scheme

One of the early proposals of a probabilistic broadcast approach for MANETs can be found in [119]. In that work Ni et al. introduce a gossiping-based approach to overcome the *broadcast storm problem* in MANETs. In that proposed scheme, a node first checks if it received the message for the first time. If that message was already received, then the rebroadcast procedure is canceled. Otherwise the node forwards the message with a predefined probability $p$ and with the probability of $1 - p$ it discards the message. In the case of $p = 1$ this scheme is equivalent with naïve flooding, that is, every node rebroadcasts the message exactly once. Because of this predefined probability $p$, this scheme is referred to as *static gossiping.*

In [119] also another scheme is introduced, the so called Counter-based Scheme. In that scheme a delayed rebroadcast is used in order to perform the rebroadcast decision based on overheard messages. Whenever a node receives a new message, it sets a randomly chosen timeout. During the timeout period a counter is incremented for every duplicate message received. After the timeout has expired, the message will only be forwarded if the counter is still below a certain threshold value.

### The Anonymous Gossip Protocol

In [235] Chandra et al. propose the *Anonymous Gossip Protocol.* The goal of that protocol is to improve the reliability of any suitable unreliable protocol. Therefore, the protocol is divided into two phases. In the first phase the unreliable multicast protocol is used to deliver the message. In the second phase the proposed gossip protocol recovers lost messages. Therefore, a node randomly selects a neighbor to which a gossip message is sent. This message includes – among others – a list with the sequence numbers of messages that the node missed. A node receiving such a message randomly decides to accept the message or to further propagate. Upon accepting a gossip message, a node uses unicast to send a gossip replay message to the source node.

### Haas's Protocol

Haas et al. introduce in [236] several probabilistic schemes in order to improve the performance of the classical *static gossip* protocol. The first protocol is called $GOSSIP1(p, k)$. $p$ is the rebroadcast probability – exactly as in the case of *static gossip* – whereas $k$ is the number of hops for which the message is rebroadcast with the probability of 1. I.e. the first $k$-hops the message is flooded and then further gossiped with probability $p$. This extension prevents that a broadcast message is dying out in the early dissemination stage.

[236] introduces a second scheme, the so called two-threshold scheme. This is an improvement for *static gossiping* based on neighbor count. Therefore, the gossip function $GOSSIP2(p1, k, p2, n)$ is used. $p1$ and $k$ are identical with the parameters of the $GOSSIP1(p, k)$ function. The novelty is the second forwarding probability $p2$ and the neighbor count threshold value $n$. A node forwards a message with probability $p1$ in the case of more than $n$ neighbors. If the number of neighbors of a node drops below this threshold $n$ then messages will be forwarded with a higher probability $p2$. The obvious advantage of this improvement is that in regions of the network with sparse connectivity messages are prevented from dying out because the forwarding probability is higher than in dense regions.

[236] also describes another improvement which tries to determine if a message is "dying out". Assuming a node has $n$ neighbors and the gossiping probability is $p$ then this node should receive every message about $p \cdot n$ times from its neighbors. If this node receives a message significantly fewer, the node will forward the message unless it has not already done so. This scheme is called $GOSSIP3(p, k, m)$, with $p$ and $k$ being the same parameters and in $GOSSIP1(p, k)$ and $m$ the threshold for the number of neighbors rebroadcasting the message. Thus, if a node has not forwarded a message, it will still do so after the timeout period if less than $m$ neighbors rebroadcast that message.

### Weighted and Slotted Persistence Broadcasting

Wisitpongphan et al. propose in [66] three broadcasting schemes, namely *Slotted 1-Persistence Broadcasting*, *Slotted p-Persistence Broadcasting*, and *Weighted p-Persistence Broadcasting*. The first scheme uses a delayed rebroadcast scheme which assigns a shorter backoff timer to distant nodes in order to maximize the per hop dissemination progress. This scheme is very similar to the delayed rebroadcast schemes already discussed in this chapter. The *Slotted p-Persistence Broadcasting* scheme is similar to the first one, with the difference that after the backoff time a node rebroadcasts the message with the probability $p$ instead of 1.

The *Weighted p-Persistence Broadcasting* scheme does not introduce a distance-based rebroadcast delay but it determines the rebroadcast probability based on the distance between the receiver of a broadcast message and its last hop. Therefore, when a node $v$ receives a broadcast message from node $u$ the following function is used to determine the gossip probability $p_{u,v}$:

$$p_{u,v} = \frac{D_{uv}}{R}$$

where $D_{uv}$ is the distance between $u$ and $v$ and $R$ is the transmission range. Using this function, distant nodes gossip with a higher probability, hence the per hop dissemination progress is maximized.

### The Distance-based Backoff with Counter-based Suppression Scheme

In [237] Oh et al. propose the so called Distance-based Backoff with Counter-based Suppression (DBCG) scheme which uses position information to select a backoff timer. The difference to other distance-based backoff timer schemes is that the backoff delay is not determined deterministically. DBCG uses a delay function based on the distance to the last forwarder which uses different statistical means for different distances. That is, a distant node gets assigned a shorter backoff delay with a higher probability than nodes near to the last sender.

The main advantage of using a hybrid distance and probabilistic scheme over simple probabilistic backoff schemes is the reduced probability that nodes access the wireless channel at the same time due to similar distances to the last forwarder. Therefore, the probability of packet collisions are minimized. The authors confirmed this point by simulations.

### The Distribution-Adaptive Distance with Channel Quality Protocol

In [238] Slavik and Mahgoub introduced the Distribution-Adaptive Distance with Channel Quality (DADCQ) protocol. This method is based on the intuition that the additional coverage achieved by a rebroadcast at a relay is proportional to the distance to other relaying nodes. It means, if a relaying node is very close to another node which already performed the rebroadcast, the additional coverage is very small. Whereas with increasing distance potentially more nodes can be reached by performing the rebroadcast. Therefore, nearby nodes are discriminated by this protocol using a random backoff timer in order to overhear the wireless channel for other rebroadcasts of that message. Upon reception of a message, a node determines the distance to the last relay and sets the random backoff timer. This is repeated until the timer expires without having received the messages from other relays. From all overheard messages the distance to the closest relay is determined. After expiration of the backoff timer the message will only be rebroadcast if the determined distance is above a certain threshold.

It is obvious, that this threshold value needs to adapt dynamically to the actual network conditions. Therefore, the authors proposed the use of two input parameters for the dynamic threshold determination function: the clustering factor of nodes and the channel quality. The first is determined by the periodical exchange of beacon messages containing the geographical position of a node. The second parameter is the relative strength of the line-of-sight signal in the Rician fading model. The authors noted that in VANETs nodes cannot measure this parameter accurately. For their evaluations they assumed that this value is known by the nodes and it can be used as input for the threshold determination function.

### 4.3.3 Hybrid Broadcast Approaches

As we have seen, deterministic broadcast approaches use several heuristics to determine a CDS which represent the relays in the broadcast scheme. Although the computation of a MCDS is NP-complete, the heuristics used allow a very good approximation of this optimal set of minimal size. Hence the deterministic broadcast schemes achieve a very high efficiency. However, this almost optimal efficiency reveals the main drawback of such approaches: they represent a single point of failure. If only one node fails to rebroadcast a message – be it because of a packet collision, outdated routing information, or other reasons – the overall reception rate could drop drastically. There are no redundant retransmissions to overcome failures.

On the other hand, probabilistic approaches are inherent redundant, but they still allow a significant reduction of the communication overhead – i.e. the number of retransmissions. In such approaches it does not matter if a node did not perform a rebroadcast, be it due to a failure or due to the probabilistic nature of the broadcast scheme. There are potentially other nodes which still relay that message, alleviating the effect of missed rebroadcasts. Thus, probabilistic approaches behave much better in the presence of wireless losses and node failures and are unaffected by node mobility [239]. But unfortunately they have also other limiting disadvantages.

As we have seen in the previous section, one of the early probabilistic approaches to improve flooding is static gossiping using a globally defined probability to forward messages [235, 236, 240]. All these variants will work best if the network characteristics are static, homogeneous, and known in advance. Otherwise they result either in a low delivery ratio or a high number of redundant messages. If e.g. the fixed forwarding probability is high and the vehicles reside in a traffic jam with a very high neighbors degree, the static gossip protocol will lead to the *broadcast storm problem* due to the high number of redundant rebroadcasts. On the other hand, in sparse networks a too low forwarding probability would result in a low forwarding ratio, allowing a message to die out very early. Thus, in such scenarios the reception ratio can drop drastically.

To overcome these problems, adaptive gossiping schemes were developed. Such basic improvements are – as we have discussed in the previous section – e.g. the *two-threshold scheme* or the *counter-based scheme*. Although all these adaptations improve the broadcast performance, they still face problems in random network topologies. For example, the presence of a very large number of neighbors to a node results in a small forwarding probability in all of these schemes. Despite of this, there could e.g. still be an isolated neighbor which can only receive the message from this node. An example of such a situation is shown in Figure 4.4.

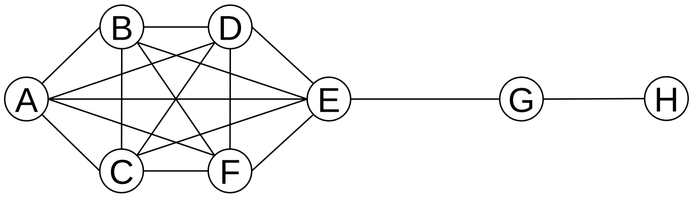


Figure 4.4: Sample topology where static gossiping fails (example taken from [187]).

When node $A$ sends a message, all nodes in its neighborhood receive it. In this example scenario only node $E$ should forward it with the probability of 1 since $E$ is the only node able to propagate the message to node $G$. If the gossiping probability is only based on the neighbors count, node $E$ will be assigned a low probability since it has many neighbors. So the broadcast message will die out with a high probability and never reach $G$ and all further nodes. If the part of the network connected only via $G$ is very large, the overall delivery ratio will drop dramatically. Such situations can occur quite regularly in dynamic networks of a certain density.

To overcome these problems, the dynamic adaptation of the forwarding probability to the actual network conditions is needed. Such an adaptation is a challenging task and is not solved adequately with simple heuristics. Therefore, recently novel probabilistic broadcast approaches were proposed which combine the strength of both protocol types, becoming this way highly adaptive to the present network conditions. We call this type of protocols *hybrid broadcast approaches*.

One of the first hybrid broadcast approaches is the so called Smart Gossip protocol, introduced in [187]. In Smart Gossip every node in the network uses neighborhood information from overheard messages to build a dependency graph. This allows the calculation of efficient forwarding probabilities at every node. To ensure building up a stable directed graph, the authors make the assumption that there are only few message originators in the whole network, because for each originator a different dependency graph has to be maintained at each node. This assumption may be sufficient in a few scenarios, but especially in the case of VANETs this is not applicable, and therefore, as shown in [118, 117] the performance of the protocol degrades massively in such environments.

To overcome these problems, a novel hybrid probabilistic broadcast was introduced by [117]. In this so called PbG one-hop neighborhood information are used together with position information of neighboring vehicles to build a local, directed dependency graph. Efficient forwarding probabilities can be calculated which adapt to current network conditions. PbG was designed for message dissemination only into one direction, e.g. for a highway traffic jam scenario, where approaching vehicles have to be informed. Thus, messages are propagated only against the driving direction. This way only one dependency graph has to be built and therefore, this protocol is denoted as the 1-Table version of PbG.

It is obvious that most VANET applications need to disseminate information in both directions of a road and cannot be restricted only to one direction. For example at an intersection, we face four road segments and therefore, a message can be distributed in four directions. In [241] a 2-Table version of the protocol was introduced suitable much better for general highway and intersections scenarios.

Furthermore, in [100] two more extension of the PbG protocol were introduced: a network density-based probability reduction and a fallback mechanism. This novel approach is known as the Optimized Position-based Gossiping (OPbG) protocol. The first mechanism reduces the forwarding probability in dense networks, thus reducing the broadcast overhead and at the same time achieving similar reception rates as the original protocol. The second extension aims to prevent message losses: A common problem in wireless networks represents the so called hidden station problem. Because IEEE 802.11p MAC layer broadcast frames are used, techniques like RTS/CTS cannot be used to avoid this problem. Especially in very dense networks the hidden station problem has a significant impact on the performance of the protocol. In such cases, the packet loss rate increases and application level requirements for the delivery ratio cannot be fulfilled any more. To overcome this problem, the second enhancement tries to determine whether a message is dying out. The enhancement works as follows. Each node receiving a new message initializes a counter which is incremented every time it overhears the same message being forwarded by some other node. If the counter is below a certain threshold after a fixed period, the message will be rebroadcast with the same probability as for the first time.

A more general gossip protocol similar to PbG was introduced in [118]. In this so called AAG protocol two-hop neighborhood information are used to calculate forwarding probabilities similar to PbG. Thus, no position information are needed which may be imprecise or even not available in some cases. Moreover, this protocol is not limited to any road topology. Furthermore, it was enhanced by a message loss avoidance mechanism in [242] which is similar to the fallback mechanism from [100]. With this extension the protocol becomes much more robust and is therefore called Robust Advanced Adaptive Gossiping (RAAG). In the mentioned work also beneficial properties of RAAG considering security are discussed and evaluated.

These novel hybrid broadcast protocols suggest very beneficial properties by combining the strength of two completely different broadcast approaches on the same time eliminating their disadvantages. Therefore, they can be regarded as a very promising approaches in order to enable efficient and reliable broadcast services in VANETs. Thus, the main focus of these thesis lies on these novel broadcast approaches in the next chapter.

## 4.4 Summary

We mentioned the problem of efficient information dissemination in VANETs. Based on an introduced classification, we have discussed several approaches with promising characteristics to cope with the challenges faced in VANETs. These broadcast approaches can be mainly divided into the two classes of *deterministic* and *probabilistic* broadcast schemes.

Deterministic approaches use heuristics based on local topology knowledge in order to determine a CDS of possibly small size. These nodes are selected as forwarders of broadcast messages enabling a very efficient information dissemination. This efficiency is the main advantage of deterministic approaches. However, such approaches lack robustness. In the presence of highly dynamic networks, error prone communication channel, and limited bandwidth (as is the case in VANETs), messages tend to die out. This results in insufficient information dissemination, prohibiting VANET applications to function correctly.

Probabilistic approaches use some probability on reception of a message to decide about the rebroadcast. This way no – or only limited – topology information is needed, compared to deterministic approaches. The main advantages of such approaches are the simplicity, the limited topology knowledge needed, and their robustness. If such rebroadcast probabilities are optimally chosen, then also high communication error rates could be compensated, at the same time enhancing the efficiency by suppressing the number of rebroadcasts. The disadvantage of these protocols is their static nature, therefore they are also called *static gossip* protocols. The gossip probability is not adequately adopted to the actual network conditions, resulting in insufficient or inefficient rebroadcasts.

As both schemes have advantages and disadvantages, we can conclude that in order to fulfill the manifold requirements of VANET applications introduced in Chapter 2, hybrid broadcast approaches are needed. Such novel approaches are developed within the scope of this thesis, representing the main contribution. Therefore, the next chapter introduces these approaches in detail. This is followed by a thorough evaluation by means of simulations in Chapter 6. The results show the applicability of the proposed protocols for efficient information dissemination in VANETs.

CHAPTER 5

# Novel Broadcast Approaches

The previous chapter showed that traditional deterministic and probabilistic broadcast approaches are insufficient for the efficient information dissemination in Vehicular Ad-hoc Networks (VANETs). This is primarily due to the high network dynamics and the tight application requirements. Although deterministic approaches are very efficient – in terms of communication overhead – they lack robustness which is a severe drawback in vehicular networks, especially when utilizing safety applications. They cannot ensure reliable information dissemination. On the other hand, traditional probabilistic approaches are static, it means they will not adapt to actual network conditions, leading either to insufficient or inefficient message dissemination.

Therefore, within the scope of this thesis, novel hybrid approaches are introduced in this chapter. These protocols are designed for highly dynamic networks like VANETs, enabling an efficient information dissemination even in the presence of extreme network conditions. As confirmed by simulations in Chapter 6, the proposed protocols reliably broadcast messages both in sparse and dense networks. They clearly outperform traditional approaches in highway and intersection scenarios with different node velocities and movement patterns.

These proposed protocols are gossip-based and use additional information in order to adapt the gossip probability dynamically to the actual network conditions. Therefore, the Position-based Gossiping (PbG) and Optimized Position-based Gossiping (OPbG) protocol use position information from neighboring vehicles, whereas the Advanced Adaptive Gossiping (AAG) and Robust Advanced Adaptive Gossiping (RAAG) protocols use two-hop neighbor topology information. These protocols are discussed in detail in the following.

## 5.1 The Position-based Gossiping Protocol

The dynamic adaptation of the forwarding probability is a challenging task in VANETs. Therefore, hybrid broadcast approaches designed for static networks like the Smart Gossip protocol suffer from serious degradation of the dissemination performance in dynamic environments as shown in [117]. As the assumptions from sensor networks like the existence of only a few broadcast message originators and static nodes cannot be transferred to VANETs, a dependency graph as built by the Smart Gossip protocol cannot be determined in the same way in vehicular networks. But such a dependency graph is a prerequisite for the determination of an accurate forwarding probability which adopts dynamically. To overcome these problems, the PbG utilizes the positions of the vehicles and the directionality of broadcast messages to build that dependency graph. This approach is detailed in the following[1].

### 5.1.1 Protocol Description

In VANETs the message propagation as well as node movement is restricted to streets. Leaving intersections aside, messages can be propagated in two directions: in and against the driving direction. Therefore, e.g. in highway scenarios it will still be possible to build a dependency graph even if all nodes are potential message originators and the network dynamics are very high. The protocol has to distinguish between these two possible dissemination directions and build up the hierarchy accordingly. For solving the problem of message propagation direction, information about node positions is used in the PbG protocol.

The dependency graph is a parent-child-sibling relationship of neighboring nodes as introduced in [187] and is hold at every node. Parents are the nodes where a node receives new messages from, siblings receive messages from the same parents and a node delivers messages to child nodes. Based on the propagation direction of messages this means, that the hierarchy can be built in two ways: in driving direction and against driving direction. If we considered typical VANET applications informing approaching vehicles about a hazardous situation, it is necessary to build the hierarchy against the driving direction. In PbG the hierarchy is built against the driving direction, since it satisfies most VANET applications.

Of course, for some scenarios it would be desirable to send messages in both directions. This is simply achieved by two different neighbor tables held at each node containing the parent-sibling-child relationships differentiated into the two possible directions.

For building the hierarchy, the PbG protocol uses a beacon service in order to exchange the needed information. Every vehicle generates beacons and sends them to their one-hop neighbors. Unlike gossip messages, beacons are not forwarded by the nodes, they are only

[1] First published in [117].

used to exchange neighborhood information for building up the parent-sibling-child relationship. Additionally, mobility is an important factor. Due to mobility, the neighborhood of a node changes frequently. Therefore, building the hierarchy must be a continuous process which is carried out in regular intervals to adapt to topology changes quickly.

To deal with fast changes we added a timestamp-based check if entries in the neighborhood table are up to date. If a node does not receive a beacon from a neighbor within a certain period it will remove the neighbor from its neighbor table. It is obvious, that in this case the hierarchy has to be adapted to the changing neighborhood. Therefore, at each reception of a beacon the originator is assigned a role (parent, sibling or child) according to the newest neighborhood information.

Listing 5.1: Pseudo code of the proposed protocol (first published in [117]).

```
Receive_Beacon(fromNode j)
{
  RemoveFromNeighborSets(j);
  if (parent(j) not in NeighborSets &&
               position(j) in driving direction){
    AddToParentSet(j);
  }
  else if (parent(j) not in NeighborSets &&
               position(j) not in driving){
    AddToChildSet(j);
  }
  else if (parent(j) in SiblingSet){
    AddToChildSet(j);
  }
  else if (parent(j) in ParentSet){
    AddToSiblingSet(j);
  }
}
```

The code listing 5.1 shows how the neighbor relationship is established step by step when a node receives a beacon message. At each reception of a packet the method *Received_Beacon* is called. First the sender is removed from the neighbor tables, which are the parent, sibling and child sets. If the parent of the sender (node $j$ in this case) is not in the neighbor tables (thus it is unknown at the receiver node) and the sender is in front of the receiving node, the sender will be inserted into the parent set. If the parent of the sender is unknown, but the sender is behind of the receiver, the sender will be inserted into the child set. When the parent of the sender is known, then depending if it is in the sibling or parent set, the sender will be added to the child or sibling set.

In the following an illustrative example for building this parent-sibling-child relationship is given. Figure 5.1 shows the initial situation. There are 4 vehicles (Nodes $A$, $B$, $C$ and $D$) and they have no information about each other so far. This means, the neighbor tables (parent, sibling and a child set) of those nodes are empty. Since every vehicle sends periodically beacons (including position information and a list with its parents), the hierarchy can be built up step by step. Assume in this example that node $D$ sends first such a beacon which

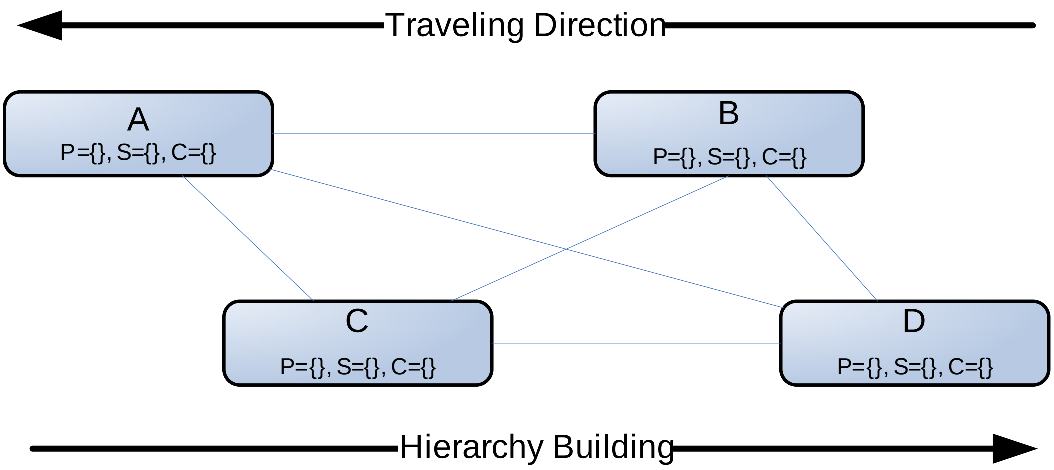


Figure 5.1: Example for building the neighbor relationships: initial situation (first published in [117]).

is received by the other three nodes. The nodes $A$, $B$ and $C$ have to determine their relation to node $D$. First, the direction to $D$ is checked. Since $D$ is behind the other nodes, it cannot be a parent node. Because the received beacon has an empty list of parents of the sender, $D$ cannot be a sibling of the other nodes. Thus, $D$ is put into the child set of vehicles $A$, $B$ and $C$.

Continuing the example, assume node $B$ sends the next beacon. The nodes $A$ and $C$ put $B$ into their child list for the same reason as before. Node $D$ determines the direction to node $B$. Since $B$ is before $D$, it cannot be a child. And because $B$ has no parents determined yet, they cannot be siblings. Thus, node $D$ adds $B$ into its parent set. Next, node $A$ sends a beacon. Nodes $B$, $C$ and $D$ receive the beacon and insert $A$ in their parent set because node $A$ has not the same parents as the other nodes (actually $A$ has no parents at all) and the position of $A$ is in front of $B$, $C$ and $D$. In the next step node $C$ sends a beacon. $A$ inserts $C$ in its child set because the parent of $C$ is $A$ itself. Nodes $B$ and $D$ have the same parent as $C$ (node $A$) and therefore they put $C$ in their sibling set. Figure 5.2 shows the updated neighbor tables after this step.

In the following a second round is considered where the nodes send in the same order as before. This will show how the topology neighborhood relationship is adapted when newer or more precise information are available. Node $D$ sends a beacon again. For node $A$ there is no change because in the beacon message $A$ is specified as a parent of $D$ and $D$ is already a child of $A$. But $B$ and $C$ put node $D$ in their sibling set because they have the same parent as $D$. Next, node $B$ sends a beacon. Again the sets of $A$ are unchanged. Node $C$

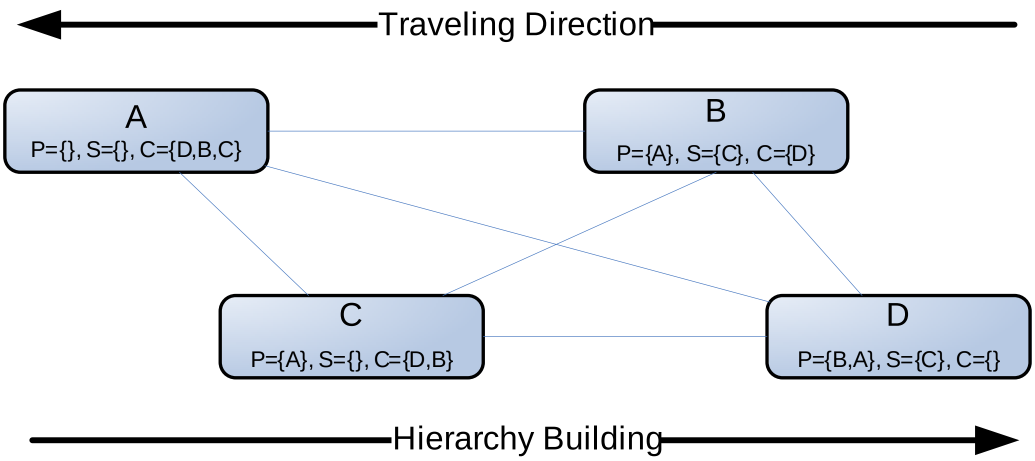


Figure 5.2: Example for building the neighbor relationships: situation after all nodes sent one beacon (first published in [117]).

and $D$ insert $B$ into their sibling sets cause they have the same parent as $B$. With further beacons the neighbor tables does not change anymore, since the relationship is already built up correctly. Figure 5.3 shows the final neighbor tables of these nodes.

Of course, due to mobility the neighbor tables can change again. Nodes leave the neighborhood of other nodes, or new nodes arrive but also a shift of the relationship based on the relative positions is possible. But through the use of beacons and timestamps for establishing the relationship, accurate neighbor relationships can be maintained even for highly mobile nodes. An evaluation of the performance for static scenarios as well as for highly mobile nodes is given in the next chapter.

### 5.1.2 Determination of the Gossip Probability

So far, the PbG protocol was described in detail, now we take a closer look at the probability determination function $prob(\#parent(c_i), \delta)$. This is the same function as used in the Smart Gossip protocol, introduced by Kyasanur et al. in [187]. The authors assume that an application can specify its reliability requirement as an average reception percentage $\tau_{arp}$. For example, an application can determine that it requires 99% reception rate. Since the actual reception rate becomes smaller with every forwarding step, it is translated into a so called per hop reception probability $\tau_{rel}$ which considers also the network diameter $\delta$ to ensure the required receptions rate also in large networks. $\tau_{rel}$ is thus the probability a node uses to forward a message. This probability can be determined by the following equation:

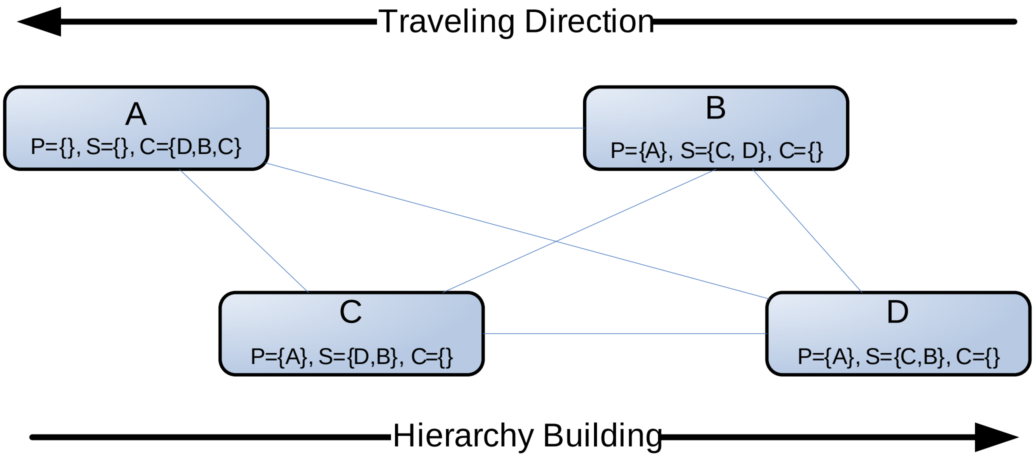


Figure 5.3: Example for building the neighbor relationships: the final neighborhood relationships (first published in [117]).

$$(\tau_{rel})^{\delta} = \tau_{arp}$$

where $\delta$ represents the diameter of the network.

If a child has only one parent then the message will have to be forwarded at least with the probability $\tau_{rel}$ (in the proposed protocol the probability is set to 1 in this case). However, in the case of more parents it is sufficient to forward with a lower probability $p_{forward}$. This probability has to be set to a value which ensures that a child receives the messages with at least the probability $\tau_{rel}$ from its parents. Knowing the number of parents ($K = \#parent(c_i)$), the forward probability can be determined with the following equation:

$$(1 - p_{forward})^{K} < (1 - \tau_{rel})$$

Using this function for probability calculation, our evaluation shows that we can achieve both a high delivery ratio and a good efficiency due to a low forwarding rate.

## 5.2 Position-based Gossiping in Intersections

In the last section the PbG protocol designed for highway scenarios was introduced. Because VANET applications are not limited to one dimensional traffic patterns, this section presents an extension of the PbG protocol[2] in order to enable the efficient dissemination of broadcast messages also in intersection scenarios.

[2]First published in [241].

### 5.2.1 Scenario Description

Intersection scenarios represent an important use-case for VANETs. Especially in metropolitan areas such road topologies are common. Characteristic for these topologies is that node densities vary from very sparse crossroads with only a few vehicles to large scale traffic jams in rush hours. Furthermore, the dissemination direction is not one-dimensional like on highways, but depends on the number of road segments. This may affect the underlying broadcast protocol as is the case with the 1-Table PbG protocol.

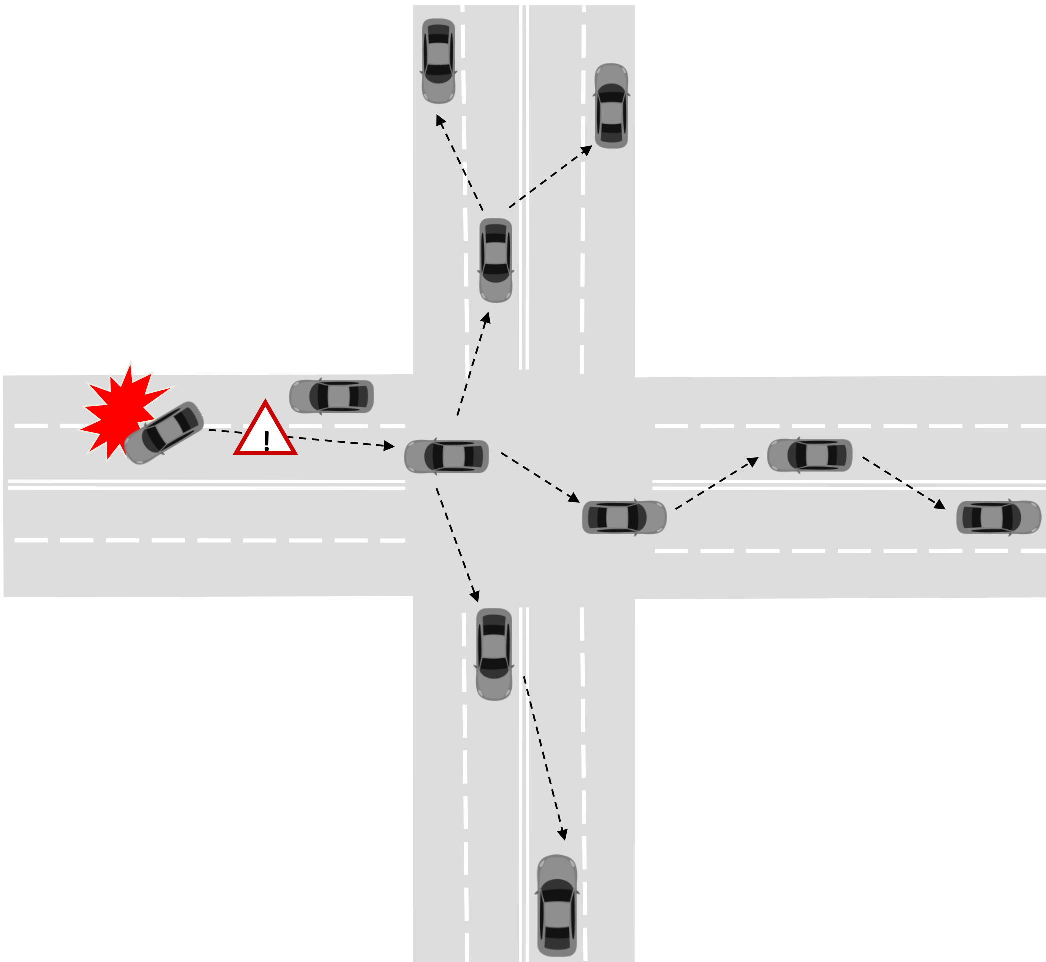

Figure 5.4: Example intersection scenario (first published in [241]).

It is obvious, that the mentioned dynamic network characteristics and the wide range of applications require a highly adaptive and efficient dissemination protocol. Consider for example a scenario depicted in Figure 5.4. The car on the left side broke down and represents a danger for arriving vehicles. Especially drivers turning into this road segment may have no line of sight and thus, the situation may become dangerous to them. By Vehicle-to-Vehicle (V2V) communications such situations can be avoided, since this information can be provided to the driver long before arriving at the dangerous area. The dissemination protocol has to assure that such a danger warning message is received by most of the relevant cars in time, thus reliability and time constraints are important in this case.

In this situation the development of a traffic jam is probable. Thus, the vehicle density may grow massively and each car detecting this new situation may originate a broadcast message, for example to perform collaborative traffic jam detection and to inform other vehicles. Without counteractive measures (as e.g. is the case of simple flooding) this results in an explosion of the number of messages leading to channel congestion and packet losses. In the worst case applications cannot operate correctly anymore. But especially in the case of traffic jams it is necessary that the communication protocol works correctly and arriving vehicles can be informed in time, thus they have a chance to choose another route, bypassing the overcrowded intersection. This would contribute to a faster resolution of the traffic jam and to an overall more efficient driving.

Concluding this subsection, it can be said that intersections are a significant part of VANET scenarios. Therefore, it is important to evaluate the efficiency and applicability of protocols for such road topologies to meet reality conditions.

### 5.2.2 Two Tables Extension

It is obvious that most VANET applications need to disseminate information in both directions of a road and cannot be restricted to only one direction. For example, at an intersection we face four road segments and therefore a message can be distributed in four directions. If a neighbor table with only one parent, sibling, and child set is used for the dependency graph – as in 1-Table PbG – the distribution of the message in the driving direction may become inefficient. Therefore, the extension we introduce in this subsection is to hold the neighborhood information in two separate tables.

Considering a vehicle driving into one direction on a road segment two tables are enough to hold the dependency graph to compute an efficient forwarding probability: one for the driving and one for the opposite direction. Of course, the moving direction of the vehicle needs to be known, e.g. from the car navigation system. Regarding the intersection scenario, each vehicle knows on which road segments it is located and in which direction it is moving. When a vehicle receives a beacon message, it handles the new information differentiated according to the two directions and stores it into the two tables. When a node receives a new broadcast message to forward, it first compares the position of the sender to its own position and uses this information to decide about the propagation direction of the message. It selects the appropriate table and forwards the message with the probability stored in the selected table – like the basic PbG would do.

The performance gain through this extension is shown by simulations in the next chapter, see 6.2.

## 5.3 Optimized Position-based Gossiping

The PbG using two tables can be applied both for highway and intersection scenarios. The protocol enables the efficient dissemination of broadcast messages. Nevertheless, there are two extensions to enhance the performance of the protocol even more. The first enhancement improves the efficiency of the protocol significantly by lowering the gossip probability in dense networks. The second extension enhances the reliability by applying a fallback mechanism in order to prevent premature message losses, thus avoiding the dying out of a broadcast message. This extended protocol is referred to as the Optimized Position-based Gossiping (OPbG) protocol. These two extensions are detailed in the following[3].

### 5.3.1 Network Density Extension

While performing simulations for this work, we discovered that the network density influences the considered broadcasting schemes. In an ideal case, the broadcasting scheme should reduce the forwarding probability drastically in very dense networks, whereas in very sparse networks it should fall back to pure flooding. The PbG protocol already manages to adapt the forwarding probability dynamically according to the local network density. But since each node has only limited local information about the network topology, there is still a high redundancy in terms of number of rebroadcasts. This redundancy was also stated in [243, 238], where the AAG protocol was compared with other approaches by simulations. The AAG protocol has similar properties to the OPbG protocol, see Section 5.4 for details. We realized in our simulations that despite a lower application reception probability requirement ($\tau_{arp}$, see 5.1.2 for details), the reception rate remained much higher. Especially in dense networks $\tau_{arp}$ can be set to a much smaller value without a considerable impact on the delivery ratio. We therefore suggest to introduce an additional reduction factor *red* that depends on the network density. This reduces the overhead while still meeting the application requirements.

[3]First published in [100].

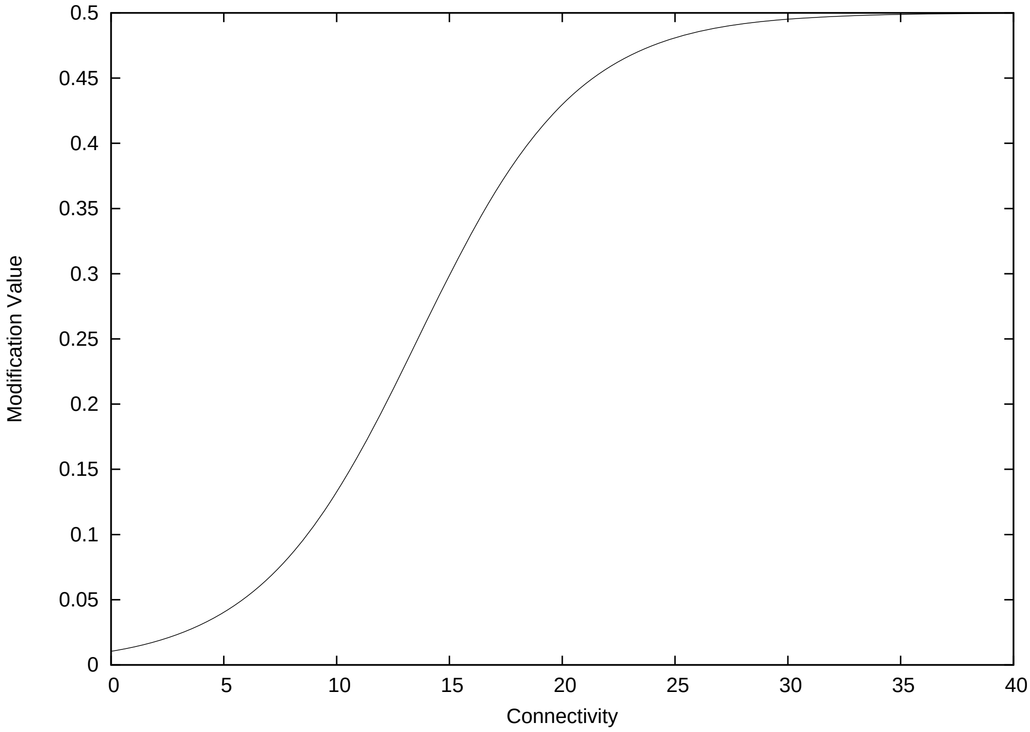


Figure 5.5: Probability reduction depending on connectivity (first published in [100]).

Using simulations, we empirically determined that given the number of neighbors ($D$) of a node, a useful reduction of the probability value ($red$) can be approximated by a logistic function:

$$red(D) = \frac{0.5}{1 + e^{-a(D-b)}}$$

where $a$ and $b$ were also discovered through extensive simulation runs. The result of this function in relation to varying neighbor degree $D$ is shown in Figure 5.5. As shown, $red$ is almost zero for low connectivity, whereas the reduction value rises up to 0.5 for higher connectivity. Applying this reduction value, the $\tau_{arp}$ value is replaced by: $\tau'_{arp} = \tau_{arp} - red$.

### 5.3.2 Message Loss Avoidance

A common problem in wireless networks represents the so called hidden station problem. Since we use Media Access Control (MAC) layer broadcast frames, techniques like Request-to-Send/Clear-to-Send (RTS/CTS) cannot be used to avoid this problem. Especially in very dense networks, the hidden station problem has a significant impact on the performance of the protocol. In such cases the packet loss rate increases and application level requirements for the delivery ratio cannot be fulfilled any more.

To overcome this problem we introduce a further enhancement of the protocol, similar to the Counter-based Scheme described in [119] which tries to determine whether a message is dying out. This is a fallback mechanism and is called Message Loss Avoidance (MLA). The enhancement works as follows. Each node receiving a new message initializes a counter which is incremented every time it overhears the same message being forwarded by some other node. The dissemination direction of an overheard message is considered and the counter is only incremented in the case the senders' position of the overheard rebroadcast lies in this direction. If the counter is below a certain threshold after a fixed period, the message will be rebroadcast with the same probability as if it was received for the first time.

Since the probability to encounter the hidden station problem increases with the distance between two nodes, the protocol limits the distance progress of such a rebroadcast. This means that a node receiving a message only initializes the counter at a distance to the sender below a threshold. This threshold is set to a low value and therefore the hop distances become shorter, but the probability is increased that all nodes receive the message.

To measure the gain introduced through these two extensions, extensive simulations were done. The results are presented in section 6.3.

## 5.4 The Advanced Adaptive Gossiping Protocol

The presented PbG protocol uses a one-table and two-table dependency graph to determine the gossip probability for one- and two-dimensional directed dissemination. In this section a more general protocol is introduced using two-hop topology information in order to calculate the gossip probability completely independent from the dissemination direction. The idea is to build the parent-child-sibling dependency graph presented in the last section solely from this topology information. This novel hybrid broadcast approach is called Advanced Adaptive Gossiping (AAG) and is detailed in the following[4].

### 5.4.1 Protocol Description

Many ad-hoc network applications require neighborhood information realized by so called *hello messages* or *beacons*. The proposed protocol makes use of such information to calculate the gossip probability. Therefore, each node periodically sends a beacon containing its neighbor table. This way all nodes know their two-hop neighborhood.

The basic idea is the following: a node $X$ receiving a broadcast message from node $S$ determines its neighbors which according to the two-hop neighborhood table could not receive that message from $S$. These are called the *child nodes* of $X$. Next, $X$ determines all common neighbors between $S$ and each child node. These nodes are potential forwarders for messages sent from $S$ to that child and are called *parents*. If the number of parents of a child is known, then a very efficient forwarding probability can be computed for that child. Finally, $X$ computes the forwarding probability for each child and forwards a message with the maximum of all calculated probability values. The higher the number of parent nodes, the lower the forwarding probability. In the case of $X$ being the single parent of a child node, it forwards the message with a probability of 1.0 since that child depends completely on $X$ for messages from $S$.

In the following a more formal definition of the algorithm is given. Let $N$ be the set of all nodes in the network and $X \in N$ be a forwarding node that receives the message $M$ from a sender $S \in N$. $S$ is a one-hop neighbor of $X$ ($S \in neighbor(X)$). The set of nodes that received the message $M$ is called $M_r$ and is equal to the neighbors of $S$. $X$ first determines its neighbors having not received the message:

$$child(X) = \{n \in N \mid n \in neighbor(X) \wedge n \notin M_r\}$$

Having the child set of node $X$, for each child $c_i \in child(X)$ all nodes are determined which

[4] First published in [118].

are possible forwarders of message $M$:

$$parent(c_i) = \{p \in N \mid p \in neighbor(c_i) \wedge p \in M_r\}$$

Based on the number of parents ($\#parent(c)$) of a child node, the probability $p_i$ for child $c_i$ is calculated as:

$$p_i = prob(\#parent(c_i), \delta)$$

where $prob(\#parent(c_i), \delta)$ is the probability determination function discussed in Section 5.1.2.

If $\#parent(c_i) = 1$ a gossip probability of 1 is assigned since node $X$ is the only parent. Finally, node $X$ forwards the message with a probability of $p = max(p_1, ..., p_n)$.

This calculation is made at every node that receives a new broadcast message. From the two-hop neighborhood information very accurate forwarding probabilities can be determined, as we consider the number of nodes that can potentially forward a message and adapt the forwarding probability dynamically based on the current topology. In the following, the mode of operation of the proposed adaptive gossip protocol is explained with the help of an illustrative example.

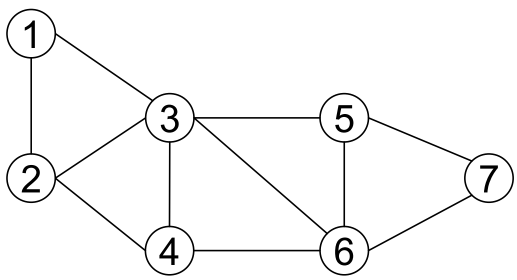


Figure 5.6: A sample topology (first published in [118]).

Assume a network topology – or a sub-network – as shown in Figur 5.6. All nodes know their two-hop neighbors because they are constantly gathering this information e.g. through beacon messages. Let node 1 be an initiator of a broadcast message, which can be received by the nodes 2 and 3. Node 2 determines its child nodes, only node 4 in this case, since node 3 has already received the message from 1. Next, node 2 searches for parents of node 4 – nodes that can forward the message to it. There are two such parent nodes: node 2 itself and node 3. Based on this information, node 2 computes the gossip probability with a parent count value of 2. Node 3 performs the same steps as node 2. Its result differs as it has nodes 5 and 6 as additional child nodes. Since it consideres itself to be the only node which can forward this message to them, its gossip probability is set to 1. After that, node

4, 5 and 6 receive the message from node 3 and perform the same steps. Duplicate messages are simply ignored.

### 5.4.2 The Robust Advanced Adaptive Gossiping Protocol

The AAG protocol is very similar to the PbG protocol. The only difference is the information used for the determination of the parent-child-sibling sets. For this reason, the enhancements introduced by the OPbG protocol can also be applied for the AAG protocol. The extensions are the suppression of the forwarding probability based on the network density and the fallback mechanism introduced to prevent the premature message losses. The application of these extensions for the AAG protocol results in the Robust Advanced Adaptive Gossiping (RAAG) protocol as introduced in [242].

The experimental results showing the performance of the RAAG protocol are presented in 6.4.

## 5.5 Summary

The two main broadcast protocol classes, the deterministic and probabilistic schemes, have different advantages and disadvantages. A characteristic for deterministic approaches is their high efficiency, whereas probabilistic approaches are more robust. Because of their disadvantages, protocols of these two classes are unsuitable for highly dynamic vehicular networks. The contribution of this chapter was the introduction of novel broadcast approaches to overcome the aforementioned problems. These so called hybrid broadcast approaches combine the positive characteristics of both protocol classes, at the same time eliminating their weaknesses.

The introduced hybrid protocols are gossip-based, this means they use some forwarding probability in order to decide at each node independently, if a rebroadcast of a message will be performed. The properties borrowed from the deterministic approaches are the information used as parameter for the probability determination function. The PbG protocol uses e.g. one-hop topology and position information, whereas the AAG-based protocols use two-hop topology knowledge. Based on this information, efficient forwarding probabilities can be calculated. Even more important, the probability is dynamically adapted to the actual network conditions.

This way, the proposed novel hybrid approaches have very beneficial properties regarding efficiency and robustness. They represent a very promising approach for the successful deployment of plenty of vehicular applications. They clearly outperform traditional broadcast approaches as shown in the next chapter where these protocols are evaluated by simulations.

# CHAPTER 6

# Evaluation

In this Chapter an extensive evaluation of the novel hybrid broadcast approaches from Chapter 5 is conducted. They are the Position-based Gossiping (PbG), Optimized Position-based Gossiping (OPbG), Advanced Adaptive Gossiping (AAG), and the Robust Advanced Adaptive Gossiping (RAAG) protocols. This evaluation is based on simulations using the Java-based network simulator JiST/SWANS [244]. As Link-/MAC layer IEEE 802.11b is used, together with the two-ray ground model and the independent noise model on the physical layer for the evaluation of the PbG protocols and their enhanced versions. This setup is motivated by the simulation parameters used in the evaluation of the Smart Gossip protocol from [187]. It allows a better comparison of the proposed and the Smart Gossip protocol. For the evaluation of the AAG protocol the additive noise model is used which allows a comparison with other protocols under more realistic conditions. The other simulation parameters together with the results are presented in the subsequent sections.

## 6.1 The Position-based Gossiping Protocol

The objective of this section is the comparison of the PbG with the Smart Gossip from [187]. This comparison was first published in [117].

The simulation setups are divided into three parts. First, we use similar simulation parameters as in [187] and make a comparison of our protocol with Smart Gossip with multiple message originators. Second, we compare the performance of the two protocols in a highway scenario. We evaluate the performance – reliability and efficiency – of these protocols for varying node densities. Third, we investigate the impact of mobility onto the PbG protocol and show the simulation results for different node speeds and densities.

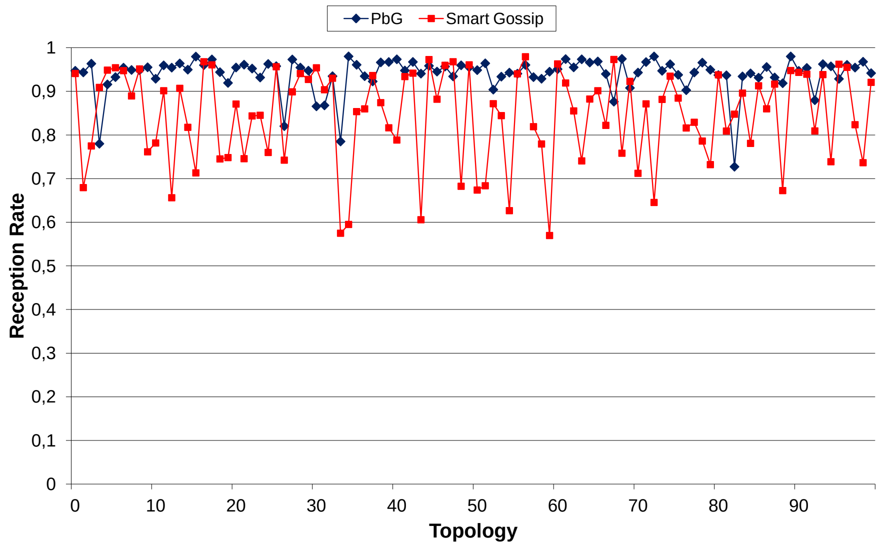


Figure 6.1: Performance evaluation of Smart Gossip and PbG with multiple message originators on a 1000 m x 1000 m field (first published in [117]).

For the first simulation, 50 nodes are randomly placed on a field with a size of 1000 x 1000 meters. The wireless transmission range is set to 280 m. Mobility is not considered in this setup, thus nodes are static. The only difference to the parameters used in [187] is the number of message originators in the network. In this setup multiple nodes can initiate broadcast messages. As it can be seen in Figure 6.1, the delivery ratio of the Smart Gossip protocol drops notably. The fluctuation of the achieved delivery ratio is high and in many cases it drops below 90%. According to the authors from [187] the delivery ratio should be about 99% with one message originator. Thus, multiple message originators have a high impact on the Smart Gossip protocol in a scenario with low node density as in this case. Our proposed protocol achieves much better results and a lower deviation at the same time. For a better comparability we included pure flooding. The average delivery ratio for the three broadcasting mechanisms in 100 simulation runs is shown in Table 6.1. As we can see the best delivery ratio is achieved with flooding. This is obvious, because all nodes retransmit the broadcast message achieving a high reliability at the cost of communication complexity. This is the main problem of flooding, especially in dense networks, the high number of redundant messages causes channel congestion, resulting in a significant drop of the delivery ratio. The delivery ratio in our proposed protocol and flooding differs only by

2%, while the original Smart Gossip ratio is in average almost 10% lower than the proposed protocol.

| Flooding | PbG | Smart Gossip |
|---|---|---|
| 95.8% | 93.9% | 84.4% |

Table 6.1: Delivery ratio flooding, PbG, and Smart Gossip (first published in [117]).

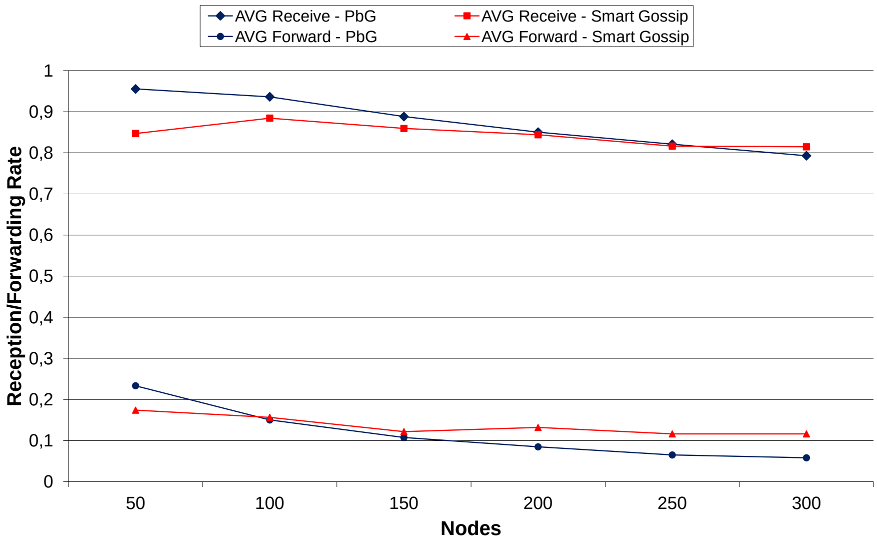


Figure 6.2: Performance evaluation of Smart Gossip and PbG with multiple message originators on a 1000 m x 10 m field (first published in [117]).

So far, a comparison of the selected broadcast protocols was given in a network topology as used in [187]. Now the focus lies on the highway scenario. Therefore, a field of 1000 x 10 meters is used representing a road segment. The other simulation parameters are the same as in the last simulations.

Figure 6.2 shows the result for varying node densities. The proposed protocol outperforms Smart Gossip for almost all evaluated node densities in terms of reliability and communication complexity. In the case of 50 nodes the Smart Gossip protocol has a lower average forwarding rate than the proposed. But it should be considered that also the average reception ratio is approximately 10% lower for the Smart Gossip protocol at this node density. Therefore, a new metric is needed that combines these two measured values – reception rate and forwarding rate – and enables a better comparison of the protocols. This combined metric can be specified in the following way:

$$Efficiency\ Rate = \frac{Reception\ Rate}{Forwarding\ Rate}$$

| | Smart Gossip | | | PbG | | |
|---|---|---|---|---|---|---|
| *Nodes* | *Reception* | *Forwarding* | *Efficiency* | *Reception* | *Forwarding* | *Efficiency* |
| 50 | 84.7% | 17.4% | 4.86 | 95.5% | 23.3% | 4.09 |
| 100 | 88.4% | 15.6% | 5.66 | 93.6% | 15.0% | 6.24 |
| 150 | 85.9% | 12.2% | 7.04 | 88.8% | 10.8% | 8.22 |
| 200 | 84.3% | 13.2% | 6.38 | 85.0% | 8.4% | 10.11 |
| 250 | 81.6% | 11.6% | 7.03 | 82.1% | 6.5% | 12.63 |
| 300 | 81.4% | 11.6% | 7.01 | 79.3% | 5.8% | 13.67 |

Table 6.2: Performance comparison between Smart Gossip and PbG (first published in [117]).

The higher the efficiency rate, the better the performance of a protocol. Table 6.2 gives an overview of the reception, forwarding and efficiency rate for both protocols. As these values show, the efficiency rate of Smart Gossip is better only at 50 nodes. But the delivery ratio at this density is approx. 10% lower. For a high reception rate at this node density, our protocol is the better choice. All other efficiency ratios show that our protocol outperforms Smart Gossip with an increasing node density. Thus, this dissemination mechanism is better suited than Smart Gossip in a highway scenario for a wide range of road traffic: it performs well in low densities and in traffic jams.

In the last simulation setup the performance of the proposed protocol is investigated with mobile nodes. These simulations were carried out only with our proposed protocol, since the Smart Gossip protocol is not designed to deal with mobility. The neighbor relationship is built up in a static way and no mechanisms were considered to hold such a hierarch up to date as it is needed in mobile environments.

For this simulation, also the highway scenario is used, thus nodes are placed into a field with a size of 1000 x 10 meters. For this evaluation the Random Waypoint (RW) mobility model was used, with different node velocities. This mobility model does not fit the realistic movements of vehicles on a highway. Nevertheless, this represents a worst case scenario because nodes are moving in arbitrary directions. A directed movement of nodes into the same direction would be more suitable for the nature of our protocol where the hierarchy is built depending on road directions. Thus, the performance of the protocol being sufficient for this case, then it should be by far better with a realistic mobility model. As Figure 6.3

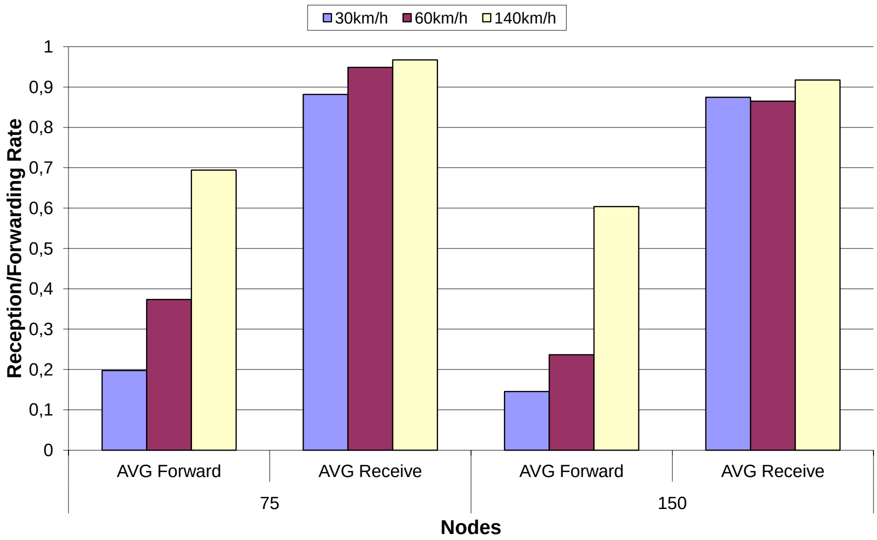


Figure 6.3: Impact of mobility on PbG (first published in [117]).

shows, mobility has only a very small impact on the delivery ratio. On the other hand, with higher node velocity the forwarding ratio increases.

It should be noted that in all simulations in this section the delivery ratio was measured by the percentage of reception of a broadcast message at all nodes. This means, a broadcast message is delivered in both directions: into driving direction and against. It is obvious that this situation is not well suited for the proposed protocol. In our approach a directed dependency between neighbors is built, thus a message should be forwarded only against the driving direction. For such a directed forwarding the proposed protocol should achieve a much better performance. We used the general case (actually the worst case) for being able to compare our approach with Smart Gossip in a scenario with multiple message originators. The next section evaluates the PbG using two tables designed for the two-dimensional dissemination.

## 6.2 Position-based Gossiping in Intersections

For the performance analysis of the 2-Table and the 1-Table PbG protocol the intersection scenario from Section 5.2.1 is used. In the following the simulation results of this scenario are presented[1].

In all simulations 150 broadcast messages are created from randomly chosen nodes. Node

[1] First published in [241].

density varies from 50 nodes up to 300 nodes. For each node density 50 simulation runs are done and the results averaged. The wireless transmission range is set to 280 meters as in the performance evaluation of the 1-Table PbG from the last section. The vehicles are randomly placed onto the roads and are static. Reception and forwarding rates are measured as indicators for the efficiency of the protocols.

In this evaluation mobility is not considered, but in the last section it was shown that the 1-Table protocol can cope very well with node mobility and this should also be valid for the 2-Table protocol.

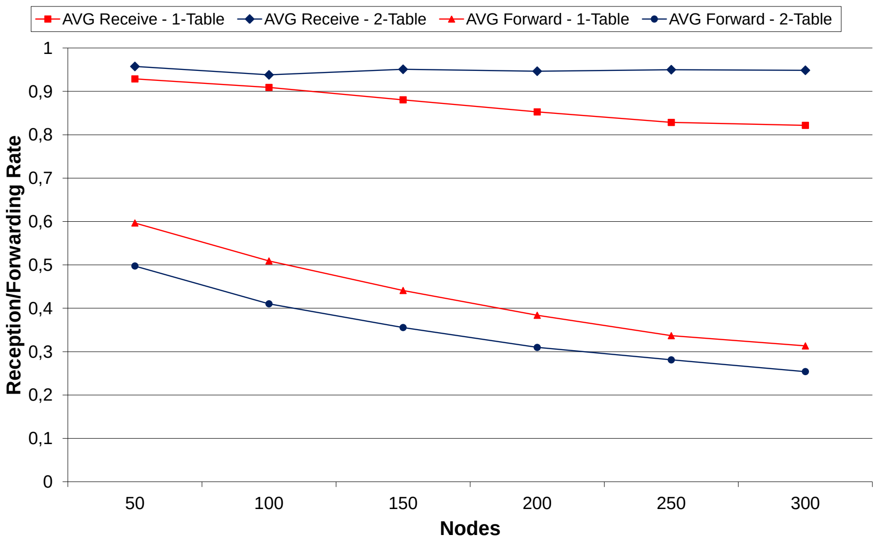


Figure 6.4: Performance evaluation of the 1-Table and 2-Table protocols in an intersection scenario (first published in [241]).

In the first simulation setup a 1000 x 1000 meters field with two crossing roads in width of 10 meters each represents the intersection. The vehicles are randomly placed onto the roads and each vehicle knows its location on the road segment. As Figure 6.4 shows, the performance difference between the 2-Table and 1-Table protocol is significant. With 50 nodes the reception rate of the 2-Table protocol is only slightly better, but the forwarding rate is about 10% better. With 300 vehicles the difference between the reception rate is highly significant: it is more than 12%. At the same time the forwarding rate of the 2-Table protocol is still about 6% lower. Regarding the overall reception rates for the different vehicle densities, the 2-Table protocol is not affected by increasing density, whereas the reception rate of the 1-Table protocol is dropping constantly.

For a better overall overview the exact values of these results are included in Table 6.3.

| | 1-Table Protocol | | | 2-Table Protocol | | |
|---|---|---|---|---|---|---|
| *Nodes* | *Reception* | *Forwarding* | *Efficiency* | *Reception* | *Forwarding* | *Efficiency* |
| 50 | 92.9% | 59.7% | 1.6 | 95.7% | 49.7% | 1.9 |
| 100 | 90.9% | 50.9% | 1.8 | 93.8% | 41.0% | 2.3 |
| 150 | 88.1% | 44.1% | 2.0 | 95.1% | 35.6% | 2.7 |
| 200 | 85.3% | 38.4% | 2.2 | 94.7% | 31.0% | 3.1 |
| 250 | 82.8% | 33.7% | 2.5 | 95.0% | 28.1% | 3.4 |
| 300 | 82.2% | 31.3% | 2.6 | 94.9% | 25.4% | 3.7 |

Table 6.3: Performance comparison between the 1-Table and 2-Table protocols (first published in [241]).

Efficiency is a combined metric as used in the last section.

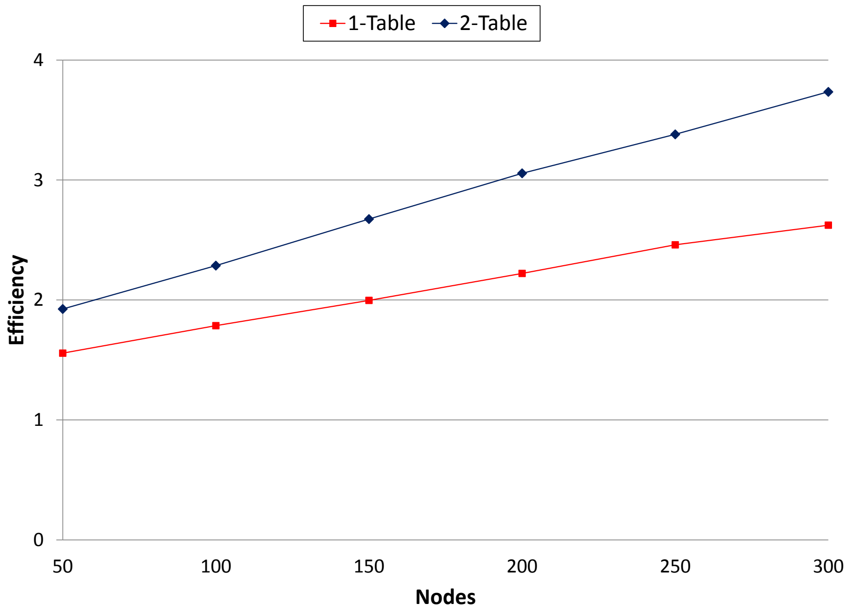


Figure 6.5: Efficiency evaluation of the 1-Table and 2-Table protocols in an intersection scenario (first published in [241]).

The efficiency metric allows a more straightforward comparison of protocols. Therefore, we show the efficiency values of the evaluated protocols with different node densities in Figure 6.5. As it can be seen, the efficiency gain of the 2-Table protocol compared to the 1-Table protocol increases with higher node densities. Having 300 nodes, the efficiency value of the 2-Table protocol is about 42% higher. Thus, it outperforms the 1-Table protocol significantly in dense networks. Especially in dense networks, an efficient dissemination protocol is indispensable to avoid bandwidth congestion and packet losses. Consider for example vehicular safety applications where the dissemination protocol has to deliver warning messages with a high reliability. Having an intersection with about 300 nodes, almost 20% of the vehicles will not receive the warning message using the 1-Table protocol. This could cause serious problems for such applications.

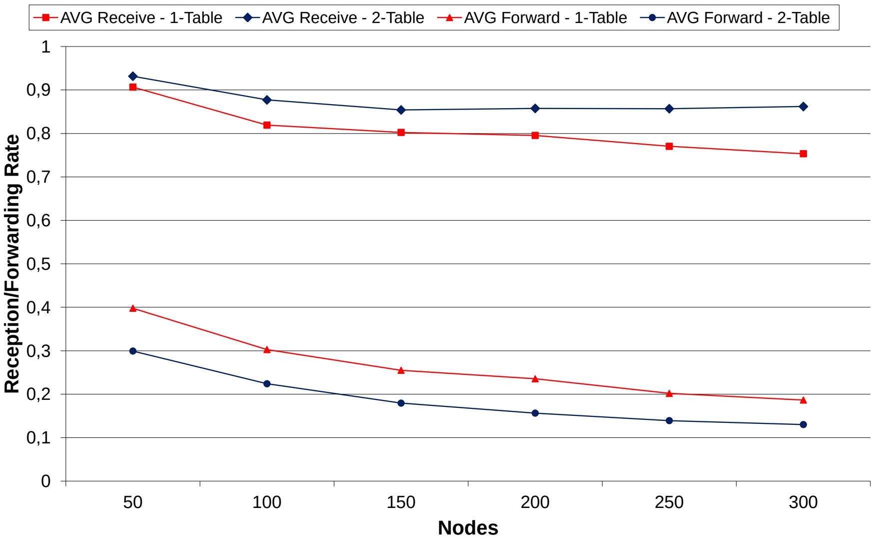


Figure 6.6: Performance evaluation of the 1-Table and 2-Table protocols in an intersection scenario with a lower reception rate requirement (first published in [241]).

For the sake of completeness, the results of another simulation setup are also presented. In Vehicular Ad-hoc Networks (VANETs) the requirements of applications to the broadcasting protocol can vary significantly. For some applications a very high delivery ratio is presumed, whereas for others, a lower delivery ratio is sufficient. Therefore, we evaluated the performance of these two protocols with a lower initial gossip probability. All parameters are the same as in the last configuration, only the forwarding probability of nodes was set to a lower value. As expected, the forwarding and reception ratio is lower as depicted in Figure 6.6. Even in this setup, as it can be seen, the 2-Table protocol outperforms the 1-Table protocol in all node densities.

## 6.3 Optimized Position-based Gossiping

In this section the performance evaluation of the extended protocol (OPbG) described in Section 5.3 is discussed in detail[2]. It is compared to the basic PbG protocol as well as the simple flooding. The radio transmission power is set to achieve a wireless transmission range

[2] First published in [100].

of 280 meters. The application reception probability requirement is set to 99% for both gossiping protocol variants. For each simulation setup, 50 simulation runs are done and the results are averaged.

In the first simulation setup an intersection scenario is used for the evaluation. Nodes are placed randomly on two crossing roads, each with a length of 1000 meters. In this setup nodes are stationary, thus node mobility is not considered yet. Each node sends one beacon message per second used to exchange neighborhood information. This information is used by the protocols to establish the neighbor tables needed for computation of the forwarding probability.

We investigate the performance of the protocol for varying node densities. Therefore, we simulate a low vehicle density intersection with 50 nodes, increasing the density up to 300 nodes in the intersection. In the middle of the beaconing each node initiates two broadcast messages, thus, with 50 vehicles 100 broadcasts are performed, whereas with 300 vehicles 600 broadcast messages are created to be delivered over the whole network.

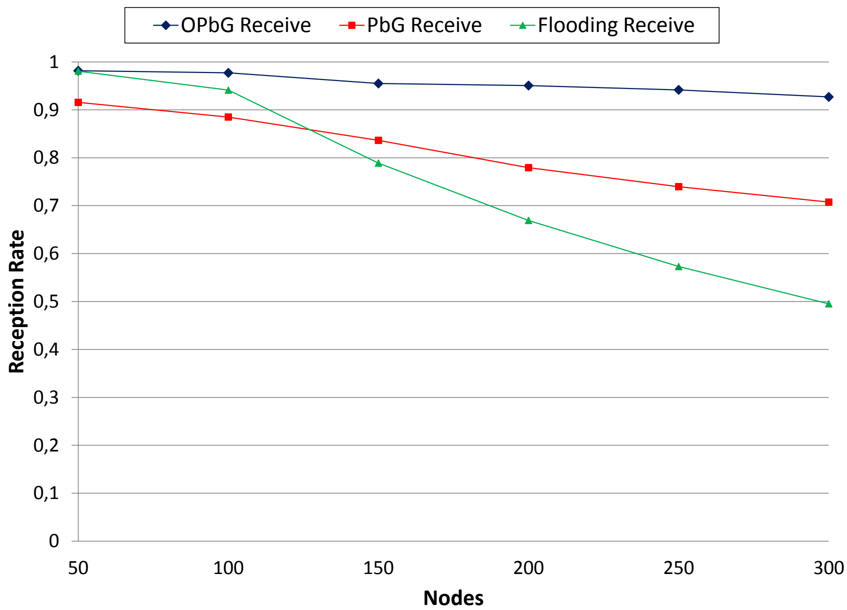


Figure 6.7: Reception rate in an intersection scenario with 50 to 300 static nodes (first published in [100]).

Figure 6.7 shows the reception percentage, i.e. the overall reception rate, for the described simulation setup. The reception rate of flooding drops significantly with growing vehicle density. With 50 vehicles flooding achieves a good delivery ratio (about 98%), but in dense

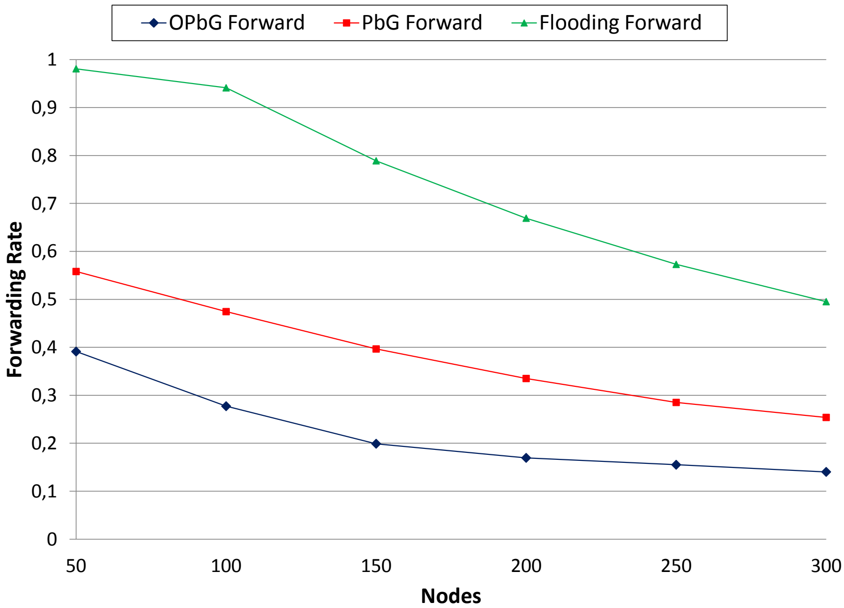


Figure 6.8: Forwarding rate in an intersection scenario with 50 to 300 static nodes (first published in [100]).

networks it drops under 50%. Such a low delivery ratio is inacceptable for most VANET applications, especially in consideration of safety applications. The PbG protocol is also notably affected by increasing node density, the delivery ratio drops to 70% with 300 vehicles. However, the OPbG protocol persistently achieves a much higher delivery ratio as the other two. For all simulated vehicle densities the reception rate lies notably above 90%. Its superiority to the two other protocols is most evident with high node densities: having 300 nodes the OPbG protocol outperforms simple flooding by more than 40% and the PbG protocol by more than 20% in terms of delivery success.

As introduced before, another key parameter of a good broadcast protocol is the forwarding rate, which denotes the quotient of the number of forwarded packets over the number of all nodes in a network. Therefore, in Figure 6.8 we present the forwarding rates of the three protocols. For flooding it is obvious that the forwarding rate is equal to the reception rate. Every message received by a node will be rebroadcast again. This is the reason why flooding has such a high communication overhead. In contrast, the two other protocols perform much better, while we see that the OPbG protocol displays the best performance. It has a up to 65% lower forwarding rate than flooding and about 20% lower than the PbG protocol for some vehicle densities.

The results for this scenario can be summarized as follows. The OPbG protocol achieves the highest delivery ratio for all node densities, whereas the other protocols are significantly affected by increasing node densities (number of broadcasts) which results in notably lower reception rates. At the same time the OPbG protocol has the lowest communication complexity since its forwarding ratio is the lowest for all vehicle densities compared to the other protocols. These characteristics render the OPbG protocol well suited for a wide range of VANET applications, where a reliable and efficient message delivery is needed.

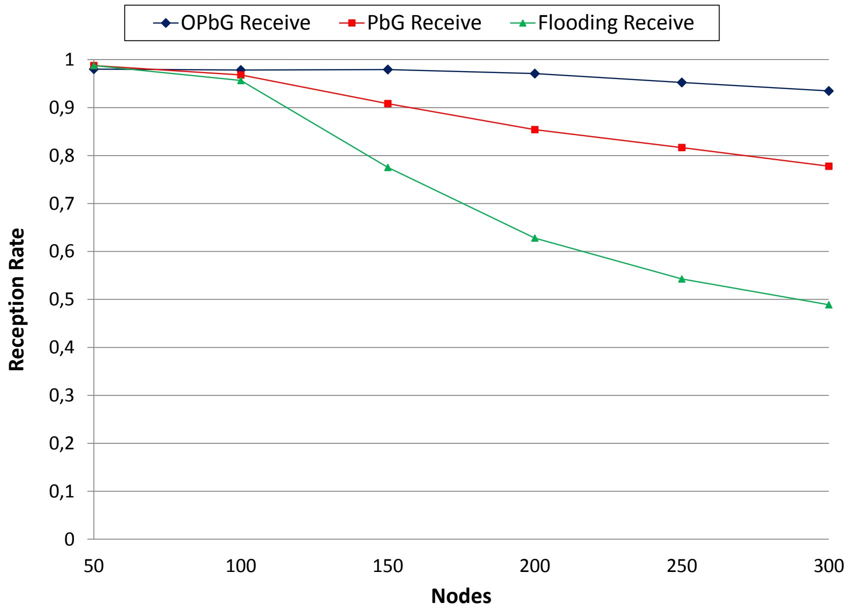


Figure 6.9: Reception rate in a highway scenario with 50 to 300 static nodes (first published in [100]).

In the next simulation setup we evaluate the performance of the protocols in a highway scenario as in the original PbG work in [117]. The difference to that evaluation is that each node initiates two broadcast messages as in the previous setup. In [117] the number of messages was fixed to 150. Figures 6.9 and 6.10 show the reception and forwarding rates respectively. As it can be seen, the PbG protocol performs better as in the intersection scenario. This corresponds to the results from [117], but since in this setup the number of broadcast messages is higher as in the PbG work, we have increased the application level probability requirement. This way we assured a higher reception rate, but as Figure 6.10 shows, the forwarding rate is higher than in [117].

Regarding flooding and our optimized protocol, the results are similar to the previous setup. Due to the high message redundancy in consequence of flooding, the reception rate

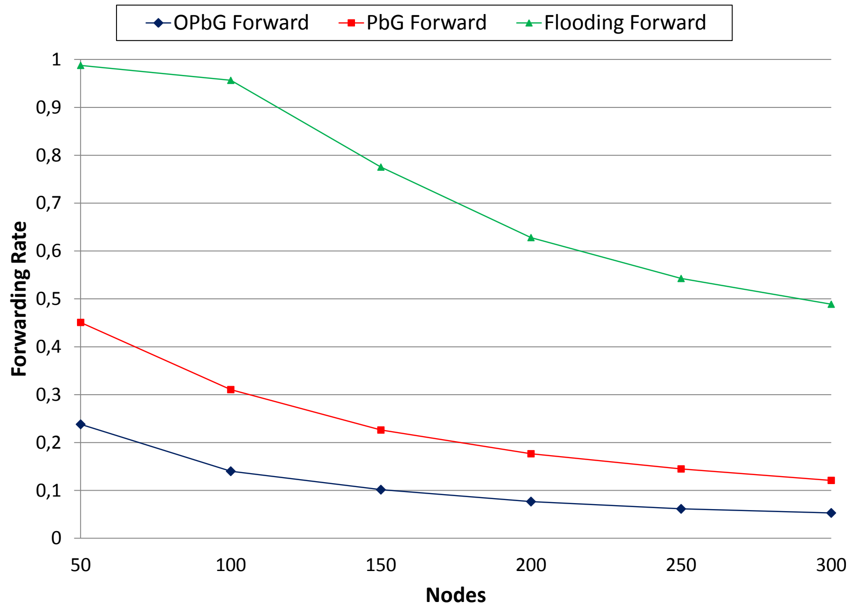


Figure 6.10: Forwarding rate in a highway scenario with 50 to 300 static nodes (first published in [100]).

drops drastically with higher vehicle densities. Also in this setup the proposed protocol achieves the best overall performance: higher reception rates than the other two protocols for most node densities, at the same time having the lowest communication complexity.

In the last simulation setup we evaluate the performance of the protocols considering vehicle mobility. Therefore, the highway scenario from the last simulation setup is used with the difference that nodes are moving with a speed of 20 m/s. As a mobility model RW is used. This mobility model does not fit the realistic movements of vehicles on a highway. Nevertheless, this represents a worst case scenario since nodes are moving in arbitrary directions. A directed movement of nodes into the same direction would suite more to the nature of our protocol where the hierarchy is built depending on road directions. As Figure 6.11 shows, OPbG achieves a very high reception rate also in this scenario. On the other hand, PbG is notably affected by node mobility. With 300 nodes the reception rate drops below 62% percent and is more than 30% lower as the reception rate of the OPbG protocol. The results of flooding are similar to the static highway scenario. Regarding the results in Figure 6.12 we see that the forwarding rates of PbG and OPbG are higher than in the static case. But the efficiency of the OPbG protocol is still higher than that of the other protocols. One reason for the increased forwarding rate with node mobility is the outdated neighbor tables.

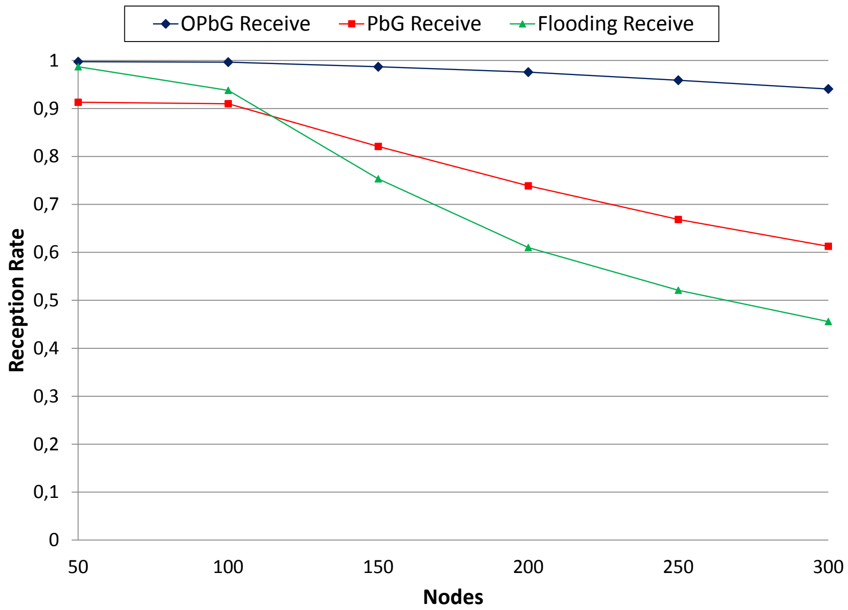


Figure 6.11: Reception rate in a highway scenario with 50 to 300 mobile nodes (node velocity: 20 m/s). First published in [100].

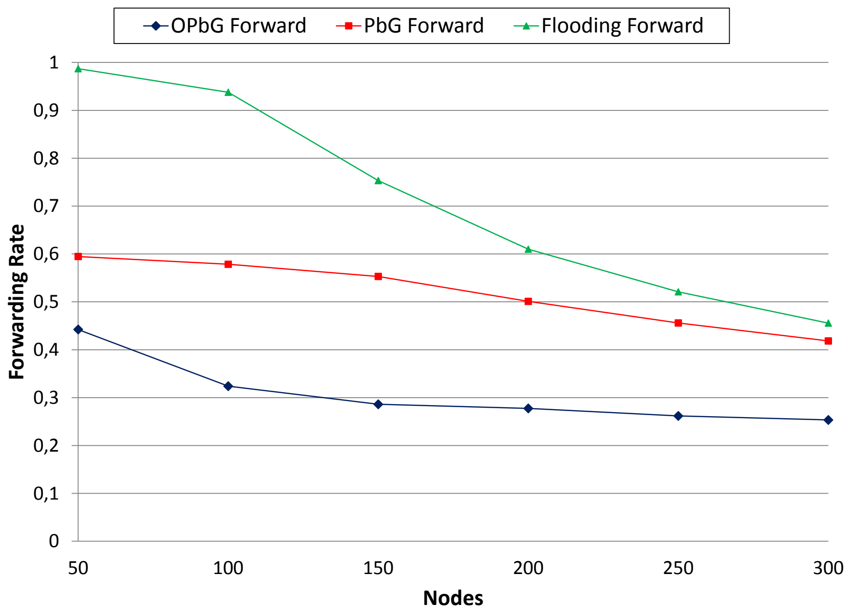


Figure 6.12: Forwarding rate in a highway scenario with 50 to 300 mobile nodes (node velocity: 20 m/s). First published in [100].

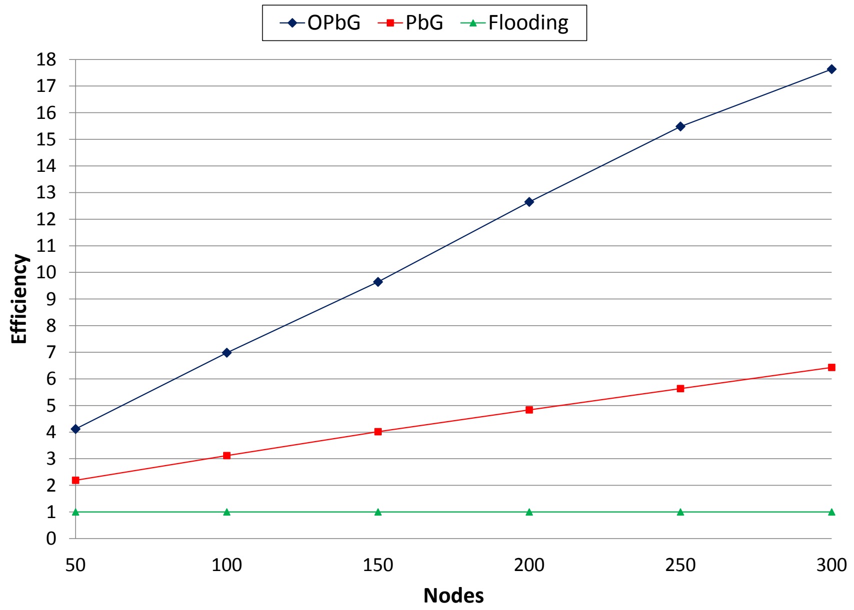


Figure 6.13: Efficiency comparison of the evaluated protocols in a static highway scenario (first published in [100]).

Figure 6.13 shows the efficiency of the three protocols for the static highway scenario. This graph gives a more comprehensive overview of the performance gain of the OPbG protocol. Having 300 nodes, the efficiency is more than 17.6 and 2.7 times higher than flooding and PbG respectively. This is a very significant performance gain and underlines the effectiveness of the enhancements introduced in this work.

## 6.4 The Advanced Adaptive Gossiping Protocol

In this section[3] we evaluate the performance of the AAG and RAAG protocols from Section 5.4. We compare these protocols to other approaches and evaluate the impact of mobility, node density, and high broadcast traffic. Therefore, we first introduce the simulation parameters and describe the two evaluated scenarios: city and highway. After that, we show that deterministic broadcast schemes are extremely affected by node mobility, thus they are inapplicable for VANETs. The remaining subsections present the results of the selected hybrid broadcast schemes in a highway and city scenario. For comparison we include also the results of naïve flooding and static gossiping. Results of the following protocols are

[3]First published in [1].

presented:

- Multipoint Relaying (MPR) [190]
- Flooding
- Static Gossiping [235, 236]
- Advanced Adaptive Gossiping (AAG) [118]
- Robust Advanced Adaptive Gossiping (RAAG) [242]

### 6.4.1 Simulation Setup

| **Parameter** | **Value** |
|---|---|
| Field | City: 1000 m x 1000 m, Highway: 3000 m x 25 m |
| Simulation Duration | 120 s |
| Broadcast Start | 5 s |
| Pathloss | Tworay |
| Noise Model | Additive |
| Transmission Range | 280 m |
| Beaconing Interval | 1 s |
| Number Messages | 3 Messages per node, max 150 |
| MlA Acknowledgements | 1 |
| MlA Replay Delay | 2.5 s |
| MlA Last Replay Offset | 100 s |
| Placement | Random |
| Static | Node Speed: 0 |
| Random Waypoint | Node Speed City: 3 – 20 m/s, Highway: 22 – 41 m/s |
| Highway Mobility | Node Speed Highway: 0 – 30 m/s |
| Simulation Runs | 20 |

Table 6.4: Simulation setup parameters (adapted from [1]).

For the evaluation of the broadcast protocols we use the JiST/SWANS [244] network simulator, including own extensions. JiST/SWANS provides a radio and MAC layer according to IEEE 802.11b. This is close to the IEEE 802.11p variant planned for vehicular communication. On the physical layer the two-ray ground model is used together with the additive noise model. The radio transmission power is set to achieve a wireless transmission range of 280 meters. For the city scenario a field size of 1000 m x 1000 m is used, whereas the simulations for the highway scenario are run on a 25 m x 3000 m field. Node density is varied from 10 up to 300 nodes, thus comparing sparse as well as dense scenarios.

The number of broadcast messages depends on the node density: every node generates one broadcast message per second (with a minimal payload), limited to a maximum count of three messages per node. The absolute number of broadcast messages is limited to 150. Thus, in a scenario with 10 nodes 30 messages are broadcast, whereas in scenarios with 50 or more nodes 150 messages are created (if not otherwise specified). This way we evaluate the protocols under low as well as under heavy network load. To hold the neighbor tables up to date beacons are used which are exchanged with a rate of 1 beacon per second. The beacon size depends on the information required by the broadcast protocol. Thus, with AAG and MPR the entire neighbor list is sent in a beacon, whereas in flooding only a message with minimal size is sent (we assume this is required by the VANET applications).

A setup is simulated over 120 s, where the broadcast of messages starts at 5 s. For the RAAG protocol, the Message Loss Avoidance (MLA) (cf. 5.3.2) mechanism is configured to await at least one acknowledgement for a sent message, otherwise the message is rebroadcast again once (if new nodes are present in the neighborhood), with a delay of 2.5 s. Messages have a timeout of 100 s and if a message was not yet acknowledged at least once, the message will be rebroadcast one more time.

To evaluate the impact of node mobility on the performance of the broadcast protocols we use three different mobility models:

- Static
- Random Waypoint (RW)
- Highway Mobility (HM)

The static model is used to measure the performance of the protocols in a best case scenario, i.e., nodes did not move at all, thus all neighborhood information are up to date. With the RW mobility model a worst case scenario is investigated where nodes move in arbitrary directions. A more realistic scenario is provided by the HM model, which is an own extension inside the JiST/SWANS framework. In this mobility model cars move in the same direction on a 4-lane highway with random speeds. They hold a safety distance to other cars, change lanes and pass slower cars, if necessary. At the end of the simulated highway the lanes are blocked by 4 cars, thus traffic congestion is simulated here. The exact parameters used for our simulations can be found in Table 6.4.

According to [245], the optimal fixed probability for static gossip is 0.7. Therefore, we use this value for the static gossip protocol in our evaluations. For each simulation setup 20 simulation runs are done and the results averaged.

### 6.4.2 Effect of Node Mobility on Deterministic Broadcast

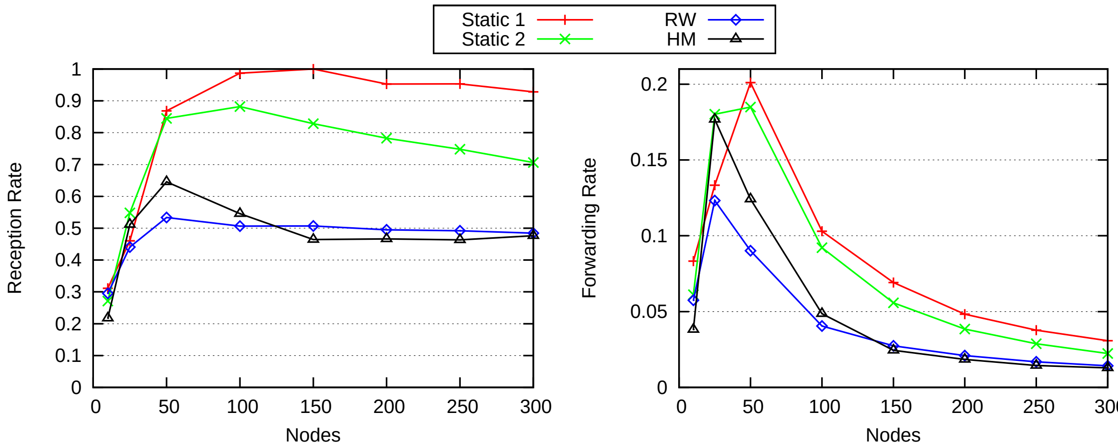


Figure 6.14: Performance of MPR in a highway scenario with different mobility models and message load (first published in [1]).

MPR was selected as a representative for deterministic protocols to evaluate the impact of node mobility. Therefore, a highway scenario with three different mobility models is used: static, RW, and HM. Because MPR lacks robustness, and therefore the number of broadcast messages extremely influences the performance of the protocol, we also simulated a scenario where only one broadcast message is initiated (Static 1). The other three simulation configurations (Static 2, RW, and HM) use the normal parameters described in 6.4.1.

Figure 6.14 shows the results of this evaluation. As we can see, in sparse networks (10 and 25 nodes) the reception rates in all four simulation setups are very low. These results are as expected, because the network is partitioned and therefore not all nodes can be reached by a broadcast without additional mechanisms. With higher node densities and only one broadcast message per simulation (Static 1), MPR achieves quite good reception rates. With 100 and 150 nodes the reception rate is almost 100% and drops slightly with increasing nodes, but stays over 90% which is an acceptable ratio. This slight decline is due to the higher overhead introduced by the beacon messages.

However, with a high number of broadcast messages (Static 2), the reception rate drops significantly in higher node densities. With 300 nodes MPR achieves only a reception rate of around 70%. This is clearly unacceptable for safety critical VANET applications. Thus, these results show that the message load has a significant influence onto deterministic protocols. Now considering mobility, we can see that with the random waypoint and HM model the reception rate drops even more drastically. With both mobility models in almost all node densities the reception rates are under 50%. Thus, deterministic approaches – without any further improvements – are inapplicable for dynamic environments like VANETs.

Regarding the forwarding rates, we can see that MPR is highly efficient, needing only around 3% or less rebroadcasts with 300 nodes. Thus, we can conclude that deterministic broadcast approaches are highly efficient but cannot meet VANET requirements in the presence of mobility and high communication overhead.

### 6.4.3 Hybrid Broadcast Approaches in a Highway Scenario

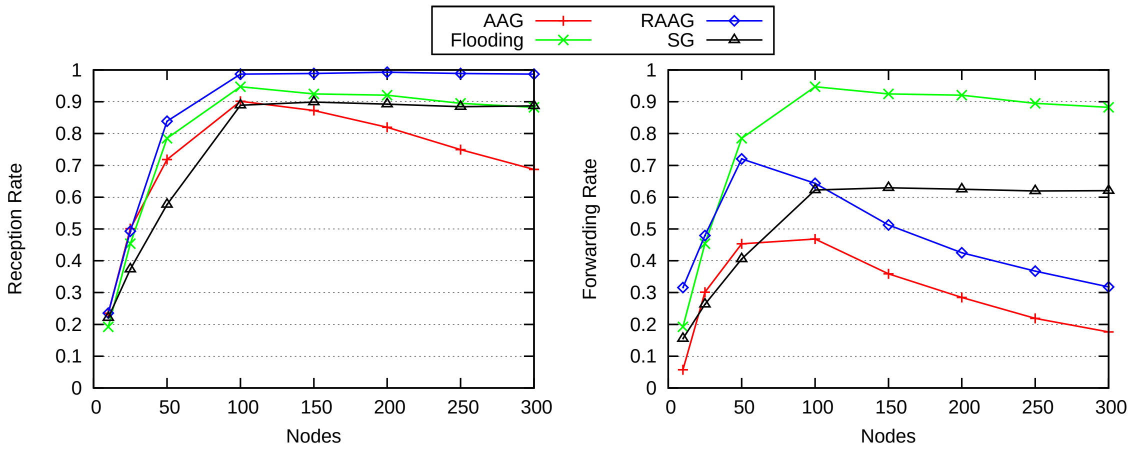


Figure 6.15: Performance of hybrid broadcast approaches in a static highway scenario (first published in [1]).

In this section we evaluate two hybrid broadcast protocols (AAG and RAAG) in a highway scenario and compare the results to flooding and static gossip (SG). Figure 6.15 shows the results for this scenario with static nodes. As we can see, with 10 nodes the reception rates of all four protocols are almost identical. The low reception rates result from the partitioned network, that is not all nodes can be reached by the broadcast message. Because the nodes are static, RAAG cannot profit from the MLA mechanism to overcome network partitions through physical movement. Whereas with 25 nodes (here the network is also not completely connected), static gossip already has a significant lower reception rate of around 10%. This gap is even bigger with 50 nodes, where static gossip has a reception rate of around 57% compared to 83% of RAAG. This is because of the static gossip probability of 70%, which is too low for sparse networks.

With higher densities, AAG significantly drops regarding the reception rate, reaching not even 70% of other vehicles in the 300 node setup. Here, static gossip and flooding achieve better reception rates, both protocols are slightly under 90%. However, RAAG clearly outperforms the other protocols, reaching almost 100% reception rates.

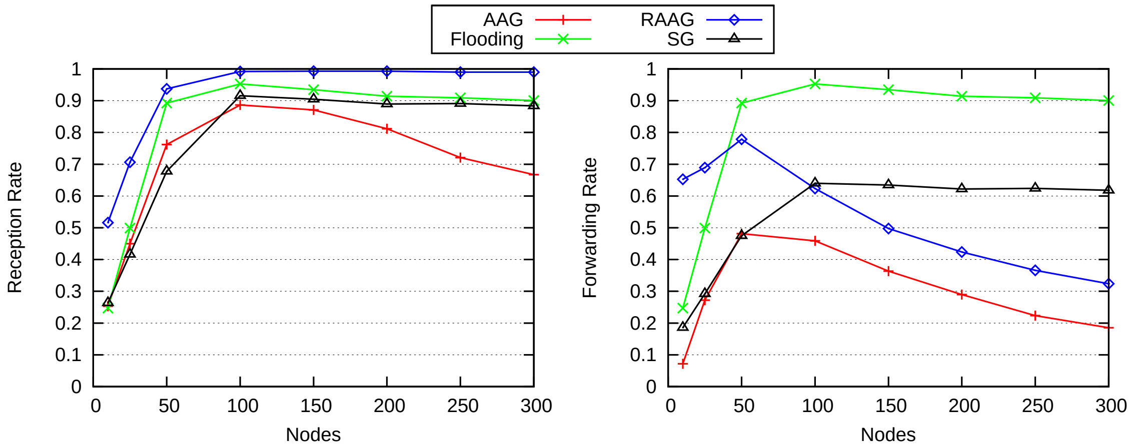


Figure 6.16: Performance of hybrid broadcast approaches in a highway scenario using the random waypoint mobility model (first published in [1]).

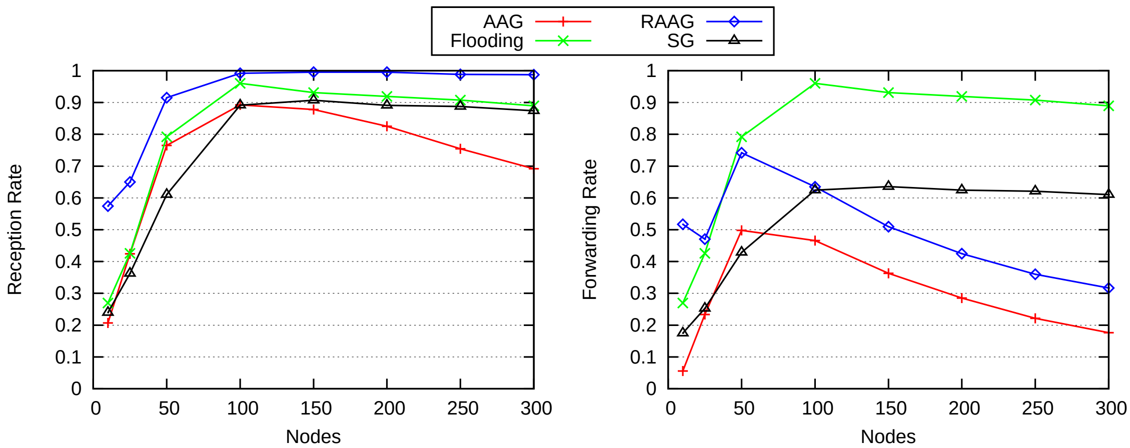


Figure 6.17: Performance of hybrid broadcast approaches in a highway scenario using the highway mobility model (first published in [1]).

Regarding the forwarding rates, we can see that flooding has the highest forwarding rates except for the scenario with 10 nodes. Here, the message loss avoidance mechanism of RAAG generates more overhead, but has not much impact onto the reception rate because the nodes are static. The rebroadcast rate of flooding is way too high in higher densities, and that is a serious problem causing the so called broadcast storm. We will discuss this effect later in a scenario with higher message load. AAG achieves the best forwarding rate, but the performance is insufficient for this scenario. Static gossip has a lower forwarding rate than RAAG with few nodes, but remains constant slightly at 60% with higher node densities. Thus, static gossip does not scale well with increasing node density. On the other hand, the forwarding rate of RAAG decreases constantly with increasing density and is constantly around 10% higher than AAG due to the message loss avoidance mechanism.

Figure 6.16 and 6.17 show the same scenario with RW and HM models. As we can see, there is almost no difference in the reception and forwarding rates compared to the static scenario. This means, that all these protocols are not affected at all by node mobility. This is a very important property which makes these protocols well suited for VANETs. The only difference compared to the static scenario is the reception and forwarding rates of the RAAG protocol in low densities. Due to node mobility, the cached messages are here physically transported and rebroadcast later. Thus, RAAG manages to overcome network partitions and achieves a much higher (at a cost of more rebroadcasts) reception rate.

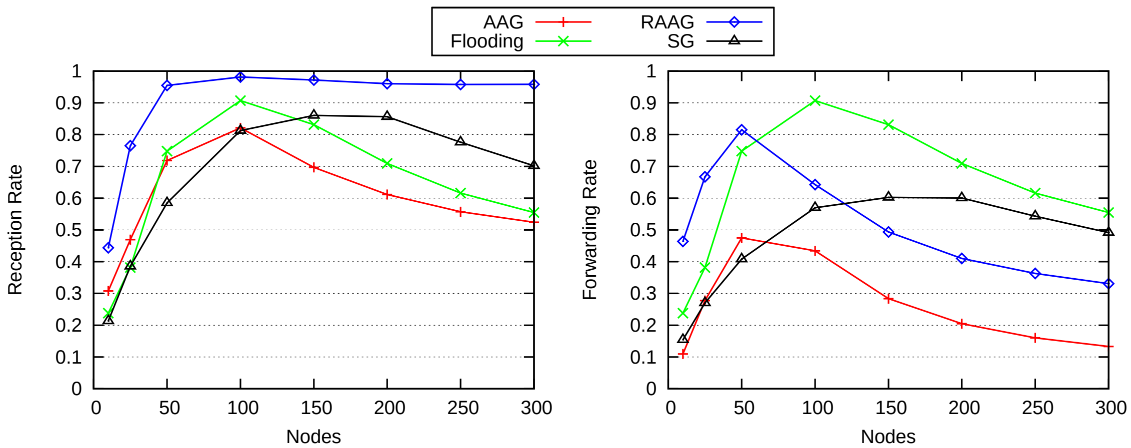


Figure 6.18: Performance of hybrid broadcast approaches in a highway scenario under high message load using the highway mobility model (first published in [1]).

In the next simulation setup we evaluate the performance of these protocols under high network load. Therefore, we increased the payload of broadcast messages to 512 bytes and raised the limit of the absolute number of messages to 300. This means, every node creates exactly 3 messages with a rate of one message per second. The results for this simulation setup are shown in Figure 6.18. As we can see, AAG and flooding cannot cope with the increasing message load, thus the reception rate is dropping significantly, reaching almost only 50% of the nodes in the 300 node setup. The reception ratio of static gossip also declines constantly with increasing node densities. Thus, these protocols are not scalable and cannot be used for VANET applications in such scenarios. Only RAAG manages to reach good reception ratios in the tested setup, and as can be seen, it clearly outperforms the other protocols. Thus we can conclude, that RAAG allows an efficient and effective dissemination also in scenarios with extreme high network load. The forwarding rates can be compared to the other results. AAG, flooding, and static gossip have lower forwarding ratios due to the packet losses.

### 6.4.4 Hybrid Broadcast Approaches in a City Scenario

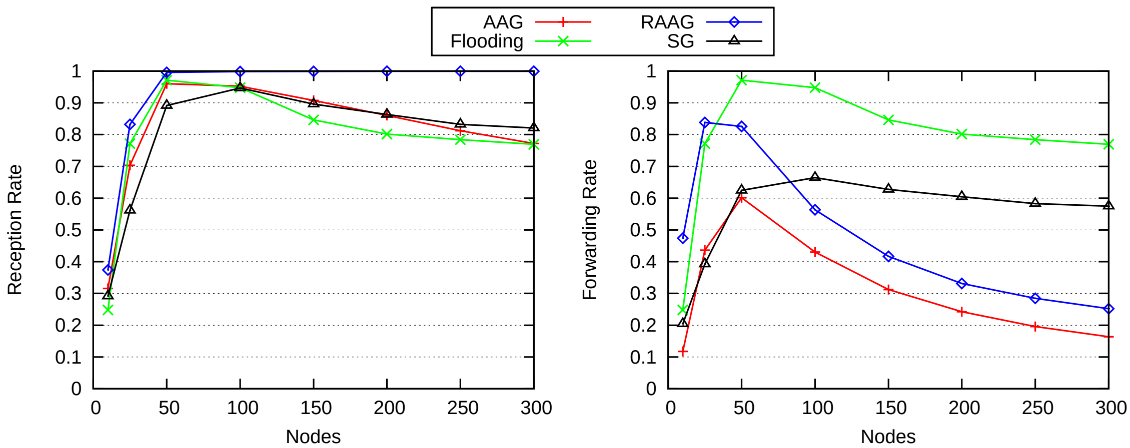


Figure 6.19: Performance of hybrid broadcast approaches in a static city scenario (first published in [1]).

For the city scenario we simulate a field of 1000 m x 1000 m with static and RW mobility. Figure 6.19 shows the results for the static scenario. As we can see, they are similar to the static highway scenario. RAAG achieves the best reception rates for all node densities, reaching almost 100% with 50 and more nodes. The reception rates of the other protocols drop constantly with increasing nodes and reach only around 80% with 300 nodes. This is clearly not sufficient for critical safety applications in VANETs. The forwarding rates are also similar to the previous scenario: flooding and static gossip have very high forwarding rates and these rates do not scale well in contrast to RAAG and AAG.

Considering the mobile city scenario shown in Figure 6.20, we can here also conclude that

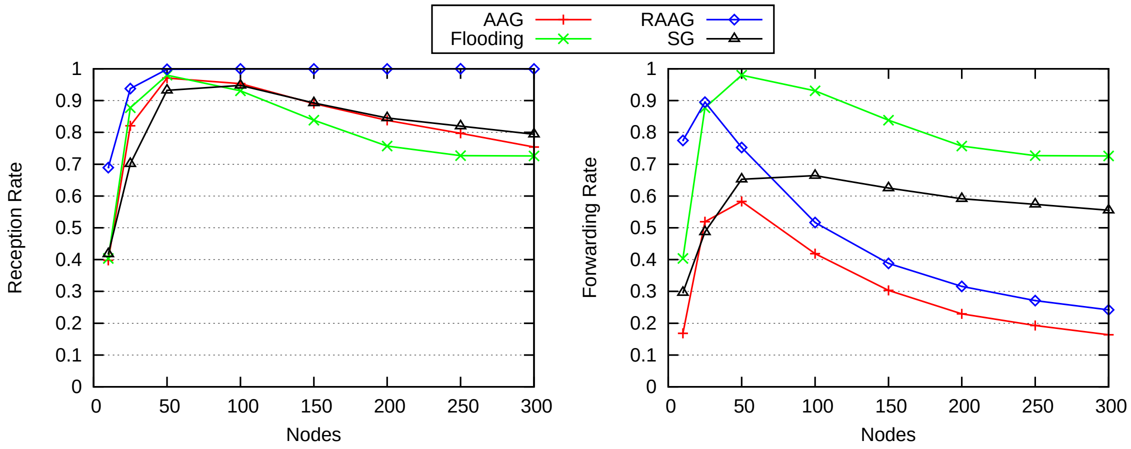


Figure 6.20: Performance of hybrid broadcast approaches in a city scenario using the random waypoint mobility model (first published in [1]).

mobility has almost no effect on these protocols. Except for the RAAG protocol, where the message loss avoidance mechanism positively benefits from the movement of nodes. In highly partitioned networks, like with 10 nodes in this figure, RAAG manages to achieve a reception rate of around 30% higher than the other protocols, or RAAG itself in a static scenario. This is a significant gain and these results underline the need of a message loss avoidance mechanism for partitioned networks.

## 6.5 Summary

This chapter evaluated the performance of different broadcast approaches in VANETs. Therefore, several approaches were investigated and compared by simulations. First, the hybrid PbG protocol designed for VANETs was compared to the Smart Gossip protocol. The simulation results show that the PbG clearly outperforms the Smart Gossip protocol originally designed for sensor networks.

After that, the applicability of the PbG in an intersection scenario was shown. Therefore, the 2-Table extension of the PbG protocol was used, which allows a more efficient dissemination in a two-dimensional scenario like intersections. The simulations underlined the performance gain of this extension.

This was followed by the evaluation of the OPbG protocol, which applies two more extensions to the original PbG protocol. These are the MLA mechanism and the network density-based gossip probability reduction. The first mechanism prevents premature message loss and helps to overcome network partitions. Thus, it increases the robustness of the underlying broadcast protocol. The second mechanism lowers the number of rebroadcasts in dense networks, thus it enhances the efficiency of the gossip protocol. The simulations showed that the performance gain was significant compared to the original protocol. This hybrid broadcast protocol also clearly outperforms flooding, in terms of reception and forwarding rates. Thus, the evaluation showed that this protocol is very well suited for VANETs in order to enable efficient information dissemination.

The last section evaluated the AAG and RAAG protocols in different scenarios and provided a profound comparison with different approaches. First, our assumption that deterministic protocols reach a very high efficiency at the cost of robustness was proven by the simulation results. Therefore, the MPR protocol was chosen as a representative of deterministic broadcast approaches. The simulations clearly showed the degradation of the reception rates due to node mobility and high message load. It can be concluded that deterministic broadcast approaches cannot be applied without additional enhancements for VANETs. This was followed by an extensive comparison of the AAG, RAAG, static gossip, and flooding protocols in different scenarios, mobility models, and network load. The results show that the proposed RAAG protocol significantly outperforms the other approaches in almost all scenarios. Its reception rates remains constantly high even in very dense networks while lowering the forwarding rates adaptively. The results showed, that due to the MLA mechanism the RAAG protocol is also able to overcome network partitions. We can conclude that these outstanding characteristics allow this protocol to fulfill the wide range of VANET application requirements.

CHAPTER 7

# Summary

Vehicular Ad-hoc Networks (VANETs) are an enabling technology for a wide range of applications. The envisioned applications make driving more safe, efficient, and entertaining. Because of different requirements of such applications, the highly dynamic network conditions, and due to the limited bandwidth of the wireless medium, the dissemination of messages in VANETs is a challenging task. But an efficient information dissemination is a prerequisite for such applications. This thesis addressed the problem of efficient information dissemination in VANETs and introduced novel hybrid broadcast approaches in order to enable such services. The next section summarizes the contribution of this thesis, followed by an outlook of topics to be addressed in future works. Finally, the thesis is completed by a brief conclusion.

## 7.1 Results and Contributions

For being able to solve the problem of efficient information dissemination in VANETs, first the application level requirements onto the communication protocols need to be known. Therefore, the first contribution of this thesis was the identification of these requirements in the applications chapter. Moreover, a combined classification of applications based on both their purpose and the communication requirements was introduced. The results are the basis for the further steps carried out on this topic in this work.

The chapter about vehicular communications started with the preliminaries of wireless communications for vehicular networks and gave a high level overview of that topic. A mapping of the previously identified application requirements onto network attributes was provided. Based on this mapping, a classification of VANET communication mechanisms from a network perspective was given. This was followed by the identification of more advanced communication patterns, which are build from those basic patterns identified in the classification. The chapter was completed by the identification of vehicular network characteristics and of non-functional requirements.

The chapter about broadcast in ad-hoc networks started our in-depth investigation of efficient broadcast mechanisms for VANETs. The main contribution was the introduction of a classification of broadcast approaches and the extensive review of existing deterministic, probabilistic, and hybrid broadcast approaches. As this review shows, deterministic approaches are very efficient – in terms of communication overhead – whereas probabilistic approaches are much more robust. We also showed that hybrid broadcast approaches combine these advantages at the same time eliminating their weaknesses.

The main contribution of this thesis is the introduction of such novel hybrid broadcast approaches designed for VANETs. We introduced a position-based scheme which builds a dependency graph based on geographical position information of one-hop neighbors. It allows the calculation of efficient forward probabilities, which dynamically adapt to the actual network conditions. This so called Position-based Gossiping (PbG) was originally designed to disseminate messages into one direction on a highway. In order to enable a two-dimensional dissemination – as is the case in intersections – we introduced an extension which uses a second table. A more general gossip approach was introduced with the Advanced Adaptive Gossiping (AAG) protocol. This protocol uses two-hop neighbor information to build that dependency graph dynamically at the reception of a broadcast message. Thus, it allows an optimal calculation of the gossip probability, independently on the dissemination direction.

For both, the PbG and the AAG protocols two extensions were introduced: a network density-based reduction of the gossip probability and a Message Loss Avoidance (MLA) mechanism. The first extension enhances the efficiency by reducing redundant retransmissions in dense networks. The MLA enhances the reliability of the broadcast protocol by retransmitting a message tending to die out. The extended versions of these protocols are called Optimized Position-based Gossiping (OPbG) and Robust Advanced Adaptive Gossiping (RAAG). The evaluation chapter presented the simulation results of these protocols. Simulations also showed that deterministic approaches are immensely affected by node mobility and message loss. That evaluation also revealed that pure flooding leads to the so called *broadcast storm problem* and that *static gossip* is not applicable for dynamic networks like VANETs. The simulations confirmed our assumptions and showed that the proposed RAAG protocol clearly outperforms other broadcast approaches.

RAAG achieves very promising results in sparse as well as in dense networks. We showed that the message loss avoidance mechanism yields a significant performance gain in sparse scenarios and increases the robustness of the protocol also in dense networks. Moreover, RAAG is not affected by node mobility which is a mandatory property of VANET protocols. Thus, we can conclude that RAAG is predestinated for dynamic networks like VANETs and satisfies the application requirements of such networks. This applies even in the presence of safety applications which impose very severe requirements onto the communication systems.

## 7.2 Outlook

Although the presented results are very promising, there are some issues to be addressed in future works. First of all, RAAG requires two-hop neighborhood information which increases the payload of beacon messages. We aim to reduce this required knowledge to one-hop neighbors, similar to the PbG protocol but in a more general way. Also the beacon rate could be adopted dynamically, e.g. based on the node's velocity. When nodes are static – as is the case e.g. in a traffic jam – the network topology changes much slower compared to scenarios which high node velocities. Thus, in such scenarios it is sufficient to beacon at a significant lower rate.

During our research, we noticed that in VANETs many broadcast approaches apply a deferred forwarding of a message in order to optimize the forwarding decision based on overheard rebroadcasts of other nodes. Such an orthogonal enhancement could also be applied to the proposed RAAG protocol. Nodes with a higher gossip probability could be assigned a shorter delay time compared to nodes with a low gossip probability. Based on the overheard messages in the delay period, a node could stop the rebroadcast process if no additional nodes can be reached.

Another topic is the evaluation of the performance of RAAG in the presence of pseudonym changes, which may have a significant effect on broadcast protocols. Because the RAAG protocol is very reliable, we assume that such pseudonym changes will not have a significant impact, but this has to be proven by simulations.

Also a detailed evaluation of the MLA mechanism in partitioned networks and its optimization could result in a significant gain in delay-tolerant networking. The MLA mechanism could be e.g. extended to perform a short delayed rebroadcast in order to avoid message loss but also to apply a long termed rebroadcast to overcome network partitions.

Another interesting topic is the investigation of clustering mechanisms for the support of information dissemination. It could be beneficial, to additionally include information of the cluster structure into the calculation of the forwarding probability. For example, a gateway node could be assigned a higher gossip probability compared to a regular cluster member. Although the maintenance of a cluster structure in such highly dynamic environments is a challenging task, the combination with a gossip-based protocol could alleviate this problem.

Thus we can conclude, there are many interesting topics which still have to be addressed in the research field of efficient information dissemination in vehicular networks.

## 7.3 Conclusion

This thesis addressed the problem of efficient information dissemination in VANETs. Therefore, we provided a profound evaluation of this research topic. We showed that traditional broadcast approaches cannot fulfill the wide range of application requirements and the non-functional requirements derived from the network characteristics. Classical deterministic approaches are affected by mobility and packet loss whereas static gossip protocols will not adapt dynamically to the actual network conditions. Thus, the main contribution of this thesis is the development of novel broadcast approaches in order to support the envisioned applications for vehicular networks.

Our solutions had the following goals in order for being suitable for VANET applications: First, an efficient information dissemination, that is to minimize the number of rebroadcasts to avoid broadcast storms. Second, a high reliability, that is to ensure that possibly all vehicles in the destination region receive a message. Third, a dynamically adaptation to changing network conditions due to vehicle mobility. Therefore, the proposed solutions have to cope with high vehicle velocities, sparse and dense networks, and different road layouts.

Although it is a challenging task to achieve these goals, within the scope of this thesis we succeeded by the introduction of novel hybrid approaches. We showed that these approaches combine the advantages of several classical protocols, at the same time alleviating their disadvantages. By simulations we proved that the proposed approaches significantly outperform the existing in almost all evaluated scenarios. Thus, these novel approaches are predestinated for the deployment in highly dynamic ad-hoc networks like VANETs. The results attest that for the envisioned vehicular applications such hybrid novel protocols are needed. Car manufacturers already test inter vehicle communication and in some years the envisioned applications could become reality. Therefore, this thesis provides important groundwork in order to make driving more safe, efficient, and entertaining.

# Abbreviations

**CCH** Control Chanel . . . . . . . . . . 40

**CCW** Cooperative Collision Warning . . . . . . . . . . 47

**CDS** Connected Dominating Set . . . . . . . . . . 91

**CGR** Cooperative Glare Reduction . . . . . . . . . . 28

**CSMA/CA** Carrier Sense Multiple Access with Collision Avoidance . . . . . . . . . . 41

**CSW** Curve Speed Warning . . . . . . . . . . 21

**CTB** Clear-to-Broadcast . . . . . . . . . . 102

**CTJD** Cooperative Traffic Jam Detection . . . . . . . . . . 67

**CVHAS** Cooperative Vehicle-Highway Automation System (Platoon) . . . . . . . . . . 28

**DADCQ** Distribution-Adaptive Distance with Channel Quality . . . . . . . . . . 114

**DBCG** Distance-based Backoff with Counter-based Suppression . . . . . . . . . . 114

**DCF** Distributed Coordination Function . . . . . . . . . . 41

**DDT** Distance Defer Transmission . . . . . . . . . . 101

**DECA** Density-Aware Reliable Broadcast . . . . . . . . . . 108

**DRG** Distributed Robust GeoCast . . . . . . . . . . xiii

**DS** Dominating Set . . . . . . . . . . 92

**DSR** Dynamic Source Routing . . . . . . . . . . 59

**DSRC** Dedicated Short-Range Communications . . . . . . . . . . 39

**EDCF** Enhanced Distributed Coordination Function . . . . . . . . . . 41

**EDL** Electronic Drivers License . . . . . . . . . . 25

**EEBL** Emergency Electronic Brake Lights . . . . . . . . . . 23

**ELP** Electronic License Plate . . . . . . . . . . 25

**EPay** E-Payment . . . . . . . . . . 54

**ERGN** Enhanced Route Guidance and Navigation . . . . . . . . . . 30

**ETJW** End of Traffic Jam Warning . . . . . . . . . . 23

**LCW** Lane Change Warning ........ 20

**LDMB** Link-based Distributed Multi-hop Broadcast ........ 107

**LPSW** Low Parking Structure Warning ........ 22

**LTA** Left Turn Assistant ........ 28

**MAC** Media Access Control ........ 129

**MANET** Mobile Ad-hoc Network ........ 84

**MCDS** Minimum Connected Dominating Set ........ 91

**MDU** Map Download/Update ........ 34

**MIVC** Multi-hop Inter-Vehicle Communications ........ 47

**MLA** Message Loss Avoidance ........ 158

**MLME** MAC Layer Management Entity ........ 41

**MPR** Multipoint Relaying ........ 147

**NCTOC** Notification of Road Conditions to a Traffic Operation Center ........ 30

**NLOS** Non-Line-of-Sight ........ 42

**OBU** On Board Unit ........ 45

**OPbG** Optimized Position-based Gossiping ........ 158

**OLSR** Optimized Link State Routing ........ 59

**PAB** Position-based Adaptive Broadcast ........ 104

**PbG** Position-based Gossiping ........ 158

**PBSM** Parameterless Broadcasting from Static to Mobile ........ 103

**PCS** Pre-Crash Sensing ........ 81

**PCW** Post-Crash Warning ........ 23

**PDP** Partial Dominant Pruning ........ 99

**PDR** Packet Delivery Rate ........ 43

**PLME** Physical Layer Management Entity ........ 41

**SSMA** Stop Sign Movement Assistance ........ 28

**SSVA** Stopped or Slow Vehicle Advisor ........ 23

**SSVW** Stop Sign Violation Warning ........ 20

**SUF** Software Update/Flashing ........ 33

**SVT** Stolen Vehicles Tracking ........ 65

**TDP** Total Dominant Pruning ........ 99

**TIQ** Traffic Information Query ........ 62

**TLO** The Last One ........ 106

**TOC** Traffic Operating Center ........ 30

**TRADE** Track Detection ........ 101

**TSVW** Traffic Signal Violation Warning ........ 20

**TTL** Time to Live ........ 11

**UMB** Urban Multi-Hop Broadcast ........ 102

**URVC** Ubiquitous Roadside-Vehicle Communications ........ 48

**V2I** Vehicle-to-Infrastructure ........ 39

**V2V** Vehicle-to-Vehicle ........ 126

**V2X** Vehicle-to-Vehicle/Vehicle-to-Infrastructure ........ 13

**VANET** Vehicular Ad-hoc Network ........ 157

**VC** Vehicular Communications ........ 45

**VE** Visibility Enhancer ........ 28

**VRCW** Vehicle-based Road Condition Warning ........ 23

**VSI** Vehicle Safety Inspection ........ 25

**VVRFN** Vehicle-to-Vehicle Road Feature Notification ........ 23

**WAPC** Warning About Pedestrians Crossing ........ 20

**WAVE** Wireless Access in Vehicular Environment ........ 40

**WD** Wireless Diagnostics . . . . . . . . . . 33

**WME** WAVE Management Entity . . . . . . . . . . 41

**WSMP** WAVE Short-Message Protocol . . . . . . . . . . 41

**WWDW** Wrong Way Driver Warning . . . . . . . . . . 24

**WZW** Work Zone Warning . . . . . . . . . . 22

**ZoI** Zone of Interest . . . . . . . . . . 83

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# Previously Published Materials

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