Roadside Networks for Vehicular Communications:

Architectures, Applications, and Test Fields

Robil Daher
University of Rostock, Germany

Alexey Vinel
Tampere University of Technology, Finland

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REFERENCE

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Chapter 13

Infrastructure Assisted Data Dissemination for Vehicular Sensor Networks in Metropolitan Areas

Ayşegül Tüysüz Erman
University of Twente, The Netherlands

Arta Dilo
University of Twente, The Netherlands

Ramon S. Schwartz
University of Twente, The Netherlands

Hans Scholten
University of Twente, The Netherlands

Paul Havinga
University of Twente, The Netherlands

ABSTRACT

Vehicular Sensor Networks (VSNs) are an emerging area of research that combines technologies developed in the domains of Intelligent Transport Systems (ITS) and Wireless Sensor Networks. Data dissemination is an important aspect of these networks. It enables vehicles to share relevant sensor data about accidents, traffic load, or pollution. Several protocols are proposed for Vehicle to Vehicle (V2V) communication, but they are prone to intermittent connectivity. In this chapter, the authors propose a roadside infrastructure to ensure stable connectivity by adding vehicle to infrastructure to the V2V communication. They introduce a data dissemination protocol, Hexagonal Cell-Based Data Dissemination, adapting it for VSNs within a metropolitan area. The virtual architecture of the proposed data dissemination protocol exploits the typical radial configuration of main roads in a city, and uses them as the basis for the communication infrastructure where data and queries are stored. The design of the communication infrastructure in accordance with the road infrastructure distributes the network data in locations that are close or easily reachable by most of the vehicles. The protocol performs a geographical routing and is suitable for highly dynamic networks, supporting a high number of mobile sources and destinations of data. It ensures reliable data delivery and fast response. The authors evaluate the performance of the proposed protocol in terms of data delivery ratio and data delivery delay. The simulation results show that HexDD significantly improves the data packet delivery ratio in VANETs.

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INTRODUCTION

Traditionally, towns were built in a very specific fashion. In the center would be the church or town hall and a market square, surrounded by one or more circular roads. A number of radial roads would allow visitors to travel from the city gates in the outer wall to the center. Many modern European cities reflect this old city plan in their current street layout. And still the old circular and radial roads are the main traffic arteries in the city. Figure 1 shows the map of the city of Enschede in the Netherlands that clearly illustrates these characteristics. If one had to choose where to build a communication infrastructure in support of vehicular networks in metropolitan areas, these roads would be the prime candidates. As it is, potential support for such networks is scattered over the city in the form of GSM base stations, Wi-Fi hotspots, traffic light and the likes (see Figure 2). The result of this haphazard infrastructure is that some parts of the city have dense communication coverage while other parts have limited coverage or no coverage at all.

In the following, we propose a sensing and communication infrastructure, in support of a data dissemination protocol for Vehicular Sensor Networks (VSNs). The infrastructure consists of lampposts that are equipped with small transceivers and sensors, positioned along roads at roughly equal distances, in addition to the existing communication and traffic control infrastructure. Such implementation has many advantages. The lampposts are already in place and no new mechanical constructions to attach the radio nodes to are needed. Electricity is present in every lamppost and is available to power up the transceivers at minimal additional costs. Because existing utilities are used, disruptions during deployment are kept to a minimum.

These roadside wireless sensors form a typical static Wireless Sensor Network (WSN), which provides a full and stable coverage of a city area. This WSN has advantages compared to a vehicular network whose coverage depends on the traffic situation and is usually unevenly distributed over a city. Vehicles together with roadside sensor nodes form a hybrid network that can serve many ap-

Figure 1. OpenStreetMap of Enschede centre overlaid with a hexagonal tessellation of cell size around 70 meters

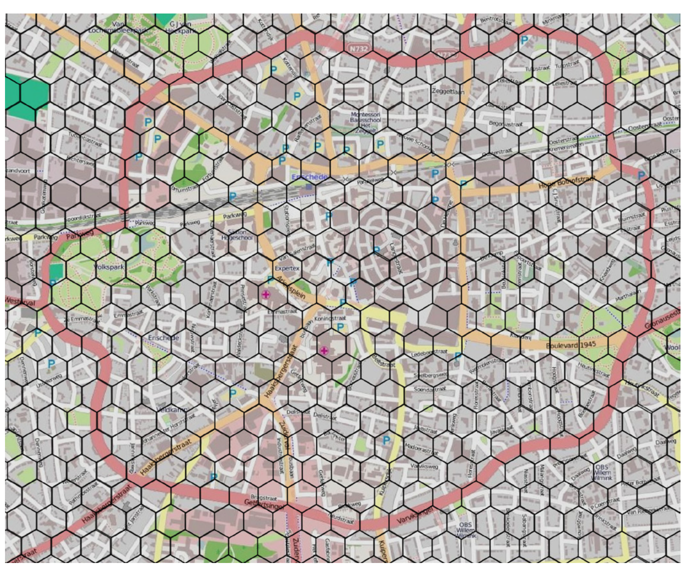
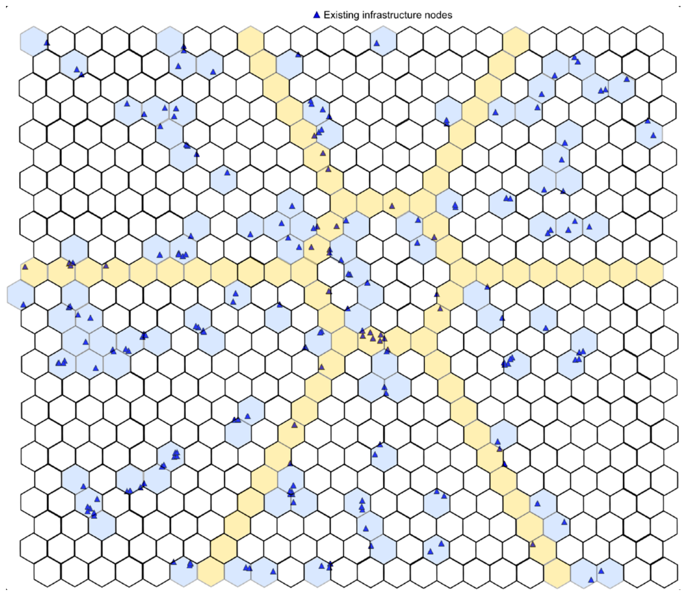


Figure 2. Virtual infrastructure of the hexagonal tessellation (white cells) overlaid on the existing infrastructure nodes; covered cells are shaded



plications, such as traffic monitoring and control, environmental monitoring, and safety warning. The proposed data dissemination protocol, called Hexagonal cell-based Data Dissemination (HexDD), can be used by these applications.

HexDD protocol was originally created for mission critical WSN applications (Tuysuz-Erman, et al., 2010), and is suitable for highly dynamic networks. The protocol is built upon a virtual hexagonal tessellation of the network area (see Figure 1). The hexagonal tessellation creates a circular structure on the city, starting from the centre, and spreading with hexagonal rings to the end of the city. Three main diagonals crossing at the centre of the city partition its area into equal parts. These three virtual lines together with a hexagonal ring (see Figure 2) form the virtual infrastructure of the HexDD protocol. The layout of this virtual infrastructure is a close approximation of a city street layout, with the main diagonals being the (main) radial roads of the city and the hexagonal ring defined by the inner ring of the city. The HexDD protocol performs routing of data and query messages by exploiting the main roads infrastructure as a communication infrastructure. The protocol provides for routing of messages, queries, or event data, without elaborating on different types or structure of information, neither on data aggregation.

We adapt the protocol for the hybrid WSN and vehicular network, and evaluate its performance in terms of latency and reliability of data delivery. The protocol is compared with a classical non-position-based ad hoc routing protocol, AODV (Perkins, Belding-Royer, & Das, 2003), and a position-based ad hoc routing protocol, GPSR (Karp & Kung, 2000).

The remainder of this chapter is organized as follows. Section 2 summarizes existing data dissemination protocols on vehicular sensor networks, together with other relevant work. The section 3 describes Vehicular Ad hoc NETworks (VANETs) applications that can benefit from the proposed protocol, followed by a realistic scenario. Section 4 elaborates further on the proposed sensing and communication infrastructure and its relation with the virtual infrastructure of the protocol. Section 5 explains the Hexagonal tessellation and Hexagonal cell-based Data Dissemination protocol. Finally, Section 6 shows the performance of the proposed data dissemination protocol, compared with other classical methods by simulations.

RELATED WORK

VANETs are a type of Mobile Ad Hoc Networks (MANETs) used for communication among vehicles and between vehicles and Roadside Units (RSUs). Since the operational principles of MANETs and VANETs resemble, most of the routing algorithms that were applicable to MANETs have been considered from VANETs, and modified for their high-speed mobility and the unpredictable nature of their movement. In a general context, routing protocols proposed for MANETs can be classified into two main categories: topology-based and geographical routing protocols (Misra, Woungang, & Misra, 2009). Topology-based routing protocols exploit topological connectivity information about the network links to establish and maintain source-destination paths. In this category, protocols are mostly classified as being either proactive or reactive.

In networks utilizing a proactive routing protocol, every node maintains one or more routing tables representing the entire topology of the network. These tables are updated regularly by means of data exchange between nodes to maintain up-to-date routing information. This process can lead to a high overhead on the network. One example of a proactive protocol is the Destination-Sequenced Distance-Vector routing (DSDV) (Perkins & Bhagwat, 1994). DSDV is based on the Bellman-Ford algorithm, however, with several modifications to make it suitable for a dynamic and self-starting network mechanism. In particular, it solves the routing loop problem. In the protocol, each entry in the routing table contains a sequence number generated by the destination, and the emitter needs to send out the next update with this number. Routing information is distributed between nodes by sending full dumps infrequently, and smaller incremental updates more frequently.

In contrast, reactive routing protocols only initiate a route discovery process when a route to a destination is required. This leads to a higher latency compared with proactive protocols, however, with the benefit of a lower overhead. One example of protocols in this class is the Ad Hoc On-Demand Distance Vector Routing (AODV) (Perkins, Belding-Royer, & Das, 2003). In AODV, a route is created on demand when a source node wants to communicate with a destination node. The route creation involves flooding a route request message and establishing, at each hop, a backward pointer (the last transmitter of the request) to the source. A reply is unicast along this path by using the backward pointers while establishing forward pointers to the destination.

In the second class of MANET protocols are the geographical routing protocols. Geographical routing relies on the geographical position of nodes to forward a packet to its destination. Because only local information is required, they do not require the establishment or maintenance of end-to-end path. In this class is the Greedy Perimeter Stateless Routing (GPSR) (Karp & Kung, 2000). GPSR uses greedy geographical forwarding from the source node to the destination node. When a node cannot find a neighbor node that is closer to the destination position than itself, a recovery strategy based on planar graph traversal is applied.

Although VANETs are a special case of MANETs, the solutions proposed for MANETs do not take into account specific characteristics of vehicular environments such as intermittent connectivity and the high mobility of nodes. For these reasons, several data dissemination solutions have been proposed specifically for vehicular environments. In the remainder of this section, we review the current state-of-the-art of data dissemination protocols in VANETs by organizing recent works in two categories: infrastructure-less and infrastructure-assisted. The former comprises solutions that deal purely with Vehicle-to-Vehicle (V2V) communication while the latter includes solutions that make use of both vehicle-to-vehicle and Vehicle-to-Infrastructure (V2I) communication.

Infrastructure-Less

In the context of infrastructure-less protocols, various solutions aim to cope with message dissemination under different traffic conditions. In dense scenarios, suppression techniques have been proposed to address the so-called broadcast storm problem. For a given broadcast message, solutions for this problem consist in finding the minimum set of nodes capable of reaching all other nodes in the network. If only nodes in this set broadcast this message, redundancy is kept to a minimum. Current solutions in MANETs are generally not optimal for VANET scenarios, especially due to the intermittent connectivity present in VANETs. Therefore, a few suppression techniques have been proposed specifically for VANETs. In Wisitpongphan et al. (2007), three broadcast suppression techniques are proposed and used in the network layer. These techniques called as Persistence Broadcasting are either time-based or probabilistic, and seek to suppress redundant rebroadcasts.

In sparse networks, the Distributed Vehicular Broadcast (DV-CAST) protocol (Tonguz, Nawaporn Wisitpongphan, & Fan Bai, 2010), the Simple and Robust Dissemination Protocol (SRD) (Schwartz, Barbosa, Meratnia, Geert Heijenk, & Scholten, 2011) and the Acknowledged Parameterless Broadcast in Static to Highly Mobile (ackPBSM) (Ros, Ruiz, & Stojmenovic, 2009) present networking solutions based on the store-carry-forward principle. DV-CAST aims to adapt its mechanism to different traffic densities. Likewise, SRD is able to operate in both sparse and dense networks and outperforms DV-CAST in terms of delivery ratio and robustness. This is achieved by using an optimized suppression technique in dense scenarios and a robust store-carry-forward protocol in sparse networks. The ackPBSM protocol relies on the use of Connected Dominating Sets (CDS) to perform the broadcast. In contrast to a directional broadcast utilized by DV-CAST and SRD, it aims to spread messages to all the surrounding neighbors.

To further improve the delivery ratio, context information was used in Kosch, Adler, Eichler, Schroth, and Strassberger (2006) and Lee and Gerla (2010). The work in Kosch et al. (2006) presents a relevance-based, altruistic communication scheme, which helps achieve scalability by optimizing the application benefit and the bandwidth usage. The benefit refers to how useful the data is to neighboring nodes according to the application managing this data, and it is calculated by considering the current context and the content of the messages. In Lee and Gerla (2010), the use of opportunistic network concepts in vehicular environments is proposed. Authors examine their opportunistic geographical routing, GeoDTN+Nav, in two examples of opportunistic routing scenarios: delay tolerant geo-inspired routing, and real time video stream multicast. Emergency related multimedia reports are sent to vehicles in disconnected platoons using network coding.

Furthermore, various applications have been proposed with the use of data dissemination schemes in VANETs. The Abiding Geocast, described in Yu and Heijenk (2008), disseminates and keeps accident or congestion information to every vehicle passing through a warning zone during the event lifetime. In Schwartz et al. (2010), authors propose the Over-the-Horizon Awareness (OTHA) protocol that provides an extended view of the traffic ahead to Driver Support Systems (DSS). The protocol relies on periodic messages sent by each vehicle. These messages are disseminated in a multi-hop fashion to other vehicles located in the road upstream, and the speed profile of the current traffic is built collaboratively.

The work in Casteigts, Nayak, and Stojmenovic (2009) addresses the main aspects of vehicular communication such as the intelligent transportation system architecture, traffic models, and existing data dissemination protocols.

Infrastructure-Assisted

The quality of services relying on vehicle-to-vehicle communication will largely depend on the available network connectivity. Therefore, especially at an initial stage of vehicular technology deployment, infrastructure will play an important role in improving the delivery ratio in sparse networks. At the time of writing, just a few solutions have proposed the use of infrastructure to assist vehicular network protocols. In the following, we describe some of these efforts.

The use of infrastructure to improve reliability in multi-hop routing in vehicular networks was proposed in Borsetti and Gozalvez (2010), He, Rutagemwa, and Shen (2008), and Shrestha, Moh, Chung, and Choi (2010). The work presented in Borsetti and Gozalvez (2010) introduces a simple and new graph representation of the road-topology map. It takes into account the relaying capabilities of roadside units for multi-hop vehicular communications, and that can be applied to existing topology-aware routing protocols. Rather than proposing a routing protocol, authors focus on the assistance of geo-routing protocols by considering roadside units with high bandwidth, high transmission range, and all interconnected through a backbone. In He et al. (2008), two novel notions are introduced to cope with link failures in vehicular networks: virtual equivalent node and differentiated reliable path. These notions are used to design the on-demand Differentiated Reliable Routing (DRR) protocol. DRR relies on both roadside units and vehicle-to-vehicle communication to adaptively discover a sufficient number of link-disjoint paths to meet the application's specific reliability. To cope with frequent disconnections in vehicular networks, the work in Shrestha et al. (2010) presents a multi-hop vehicle-to-infrastructure routing protocol, named Vertex-Based Predictive Greedy Routing (VPGR). VPGR predicts a sequence of valid vertices leveraging contextual information to forward data from a source vehicle to the infrastructure.

Also with the focus on routing, authors in Lim and Ko (2010), Peng, Abichar, and Chang (2006), and Piran (2010) aim to improve efficiency in terms of amount of data exchanged, overhead, and energy, respectively. In Lim and Ko (2010), authors propose the Multi-Hop Data Harvesting (MDH). MDH is a data-harvesting scheme that focuses on supporting applications that require multi-hop communication, such as real-time applications. In this scheme, vehicles make use of roadside sensors to send data requests and to receive data from multiple sensors. Furthermore, a data aggregation technique is used to cope with a high amount of data when using geocasting. In Peng et al. (2006), a novel routing approach, called RAR (Roadside-Aided Routing), is introduced. The proposed approach affiliates each vehicle to a sector, defined as the affiliation unit that is a road area bounded by neighboring RSUs. This can reduce significantly the affiliation overhead compared to other methods that use the concept of clusters. The protocol is also based on a single-phase routing scheme. Basically, two vehicles close to each other tend to communicate directly via ad hoc networks, whereas two vehicles close to RSUs or in different sectors tend to communicate via RSUs. The roadside units are assumed to be connected with each other by wired links or any links with high bandwidth, low delay, and low bit error rate. Therefore, the routing performance is improved by limiting ad hoc routing in a small scope, and utilizing a wired backbone network.

In contrast to routing, several works have been presented with solutions for disseminating data to multiple vehicles. In Zhao, Zhang, & Cao (2007), a data pouring and buffering paradigm for data dissemination in VANETs is proposed. Two schemes are introduced: Data Pouring (DP) and DP with Intersection Buffering (DP-IB). In DP, a data center in the infrastructure periodically broadcasts data to be disseminated and relayed by moving vehicles to pour the desired area. In DP-IB, the data poured from the source are buffered and rebroadcast at intersections. Authors in Trullols, Fiore, Casetti, Chiasserini, and Barcelo Ordinas (2010) consider the problem of deploying a given number of infrastructure nodes for disseminating information to vehicles in an urban area. The problem is formulated as a Maximum Coverage Problem (MCP) having as objective maximizing the number of vehicles in contact with infrastructure nodes. To provide a treatable solution, authors propose heuristic algorithms, which present different levels of complexity and knowledge.

To increase network connectivity in sparse networks, authors in Chawathe (2006) and Lok, Qazi, and Elmirghani (2009) proposed schemes with dropboxes. In Chawathe (2006), authors address the problem of disseminating data in sparse vehicular networks by using *dead drops* (dead letter boxes). Dead drops are wireless transceivers with storage capability that are not interconnected or connected to other network infrastructure. Such boxes, also known as dropboxes, can be used to both send and receive data to vehicles, in order to improve the overall network connectivity. This work presents a study of the optimum placement of dead drops in road intersections, and introduces an efficient greedy approximation algorithm called MCDD as a solution for such placement. The use of dropboxes is also discussed in Lok et al. (2009). Authors present a study of the impact of the following parameters when disseminating data with the help of dropboxes: end-to-end delay and Packet Dropping Probability (PDP), by varying the number of vehicles. In the same area of research, in Lochert, Scheuermann, Wewetzer, Luebke, and Mauve (2008) authors tackle both the problems of limited bandwidth and minimal initial deployment. An aggregation scheme is introduced to cope with the limited bandwidth. On the other hand, by means of a genetic algorithm, the positions for placing static roadside units are identified.

A general discussion on using sensors in vehicular environments was presented in Lee and Gerla (2010) and Nekovee (2005). In Nekovee (2005), authors discuss unique features and challenges that distinguish vehicular sensor networks from other types of ad hoc sensor networks. In addition, possible applications of wireless grids in addressing data aggregation and processing challenges are considered. In Lee and Gerla (2010), authors survey the recent vehicular sensor network developments and identify new trends. Aspects such as how sensor information is collected, stored, and harvested are evaluated considering both uses of V2V and V2I communications.

Network architectures for VSNs were subject of study in Festag et al. (2008) and Gao et al. (2010). The use of a hybrid ITS safety architecture is proposed in Festag et al. (2008). The architecture combines both vehicle-to-vehicle and vehicle-to-infrastructure sensor communication. Roadside units are connected to wireless sensor networks, thereby reducing deployment costs compared to installing dedicated roadside units. Among potential services of the hybrid communication system, the work introduces accident prevention and post-accident investigation. In addition, the main components of the system, namely, radio, networking and services, and security are described. Likewise, in Gao et al. (2010), a similar architecture is proposed with sensor nodes deployed along the roadside to collect environmental data such as data on highway conditions (e.g. potholes, cracks on the road, ice on the road, and blind spots ahead). However, the focus is on a secure data collection of such data. To achieve security, a secure symmetric key-based protocol is designed and validated with real trace data through a real implementation. The work described in Salhi, Cherif, and Senouci (2008) focuses on an architecture where an ad hoc network is operated by a telecommunication provider. The goal is to combine non-valuable individual data sensed by each vehicle, in order to obtain an overview about road conditions in a certain geographical area. The aggregated information is then sent back to a roadside unit owned by the operator via a non-free frequency (WiMax or 2.5/3G). To reduce the use of high-cost links, authors present the Clustered Gathering Protocol (CGP).

With the goal of monitoring the condition of road networks, the work described in De Zoysa, Keppitiyagama, Seneviratne, and Shihan (2007) presents BusNet, which is a public transport system (i.e. buses) equipped with acceleration sensors to monitor the road surface. The same application is proposed in Eriksson et al. (2008). A system referred to as the Pothole Patrol (P2) exploits the mobility of vehicles to opportunistically gather data from vibration and GPS sensors, and process the data to assess road surface conditions. By using a machine-learning approach, authors study the viability of the system to identify potholes and other road surface anomalies from accelerometer data. Related to this works is the research presented in Wong, Chua, and Qingyun Li (2009). Authors use wireless vehicular sensor networks for environmental monitoring. Experiments carried out with a sensor platform for air-quality monitoring demonstrate an improved spatial coverage when using vehicular sensors over static sensors. In Murty et al. (2008), an open urban-scale testbed is introduced, in the effort to support novel research and application developments in wireless and vehicular sensor networks. The testbed called CitySense consists of several Linux-based embedded PCs outfitted with dual 802.11 a/b/g radios and various sensors, mounted on buildings and streetlights across the city of Cambridge.

Comparisons

Table 1 gives an overview of the abovementioned works that are more similar to our proposal in this chapter. From this overview, we can outline that existing approaches propose either a routing strategy or architecture for VANET applications. There is only one combined effort of routing and infrastructure (i.e. RAR) which assumes a wired link between RSUs of the backbone network. As it can be observed from the table, we can classify the routing protocols into three subclasses:

1. Broadcasting,
2. Geocasting, and
3. Unicasting.

In this chapter, we propose a unicast routing based on location information of the vehicles and RSUs.

The HexDD protocol has the following advantages over the existing works:

1. It proposes the use of an inexpensive network composed of small sensor nodes to be deployed in already existing infrastructure. Such approach can decrease deployment costs compared to installing a fixed powered roadside infrastructure as proposed, for example, in Borsetti and Gozalvez (2010) and Peng et al. (2006). Although the use of wireless sensor networks has been proposed in Festag et al. (2008) and Gao et al. (2010), these works have focused on different aspects, namely, architecture and security. In contrast, HexDD focuses on routing efficiency and robustness.
2. Considering the advantages of using an infrastructure-assisted approach, HexDD relies on a virtual infrastructure called 'hexagonal tessellation.' Due to its optimized topology, hexagonal tessellation allows for an efficient geographical routing of event messages to any vehicle in the network.
3. HexDD considers end-to-end wireless communication. RSUs also communicate wirelessly via sensors attached to them.
4. HexDD makes the system resistant to node failures in the virtual infrastructure and

supports quick routing around holes in the network.

5. HexDD has the unique feature of leveraging the original layout of the city to build its virtual infrastructure. This allows for an improved delivery ratio and end-to-end delay.

In particular, we consider in this work the case of European cities, where circular and radial roads surrounds the city center. This represents a very distinct approach when compared to other works in the current literature.

POSSIBLE APPLICATIONS

Vehicular sensor networks serve as means for effectively monitoring the physical world (Lee & Gerla, 2010). Vehicles continuously gather, process, and disseminate relevant sensor data. Such networks allow for the emergence of several new applications. Among potential applications are:

- **Traffic Monitoring and Control:** Sensors deployed in both vehicles and roadside units can be used to gather information such as the speed and position of vehicles to accurately estimate the current traffic condition. Such traffic information can be combined and sent to a central authority point such as the city hall whenever requested. In addition, traffic lights equipped with sensors nodes can request live traffic information from vehicles to control the time duration of each light adaptively to the current traffic.
- **Environment Monitoring:** A central point can send a query for data obtained from chemical sensors, installed both in vehicles and in roadside units. Such data, combined, can provide a global estimate of the level of pollution in different regions of the city. Furthermore, sensors that are able to detect vibrations during the ride can generate estimates about the conditions of the road.
- **Safety Warnings:** Vehicle communication has the potential to complement internal on-board sensors (cameras or radars) to detect and warn drivers about hazardous situations when a vision beyond what sensors can provide is required. When a radio gap is present, roadside units can be used to store and later forward the corresponding data to potential interested vehicles and authorities.

Motivating Scenario

The scale of thousands of vehicles used as sensors collecting data is almost beyond imagination. Data is collected in places were previously no measurements were taken, thus broadening the scale and scope of information gathering considerably. Sharing and combining information collected by large numbers of cars will reveal patterns that were previously invisible. Acting on this newfound information, the city's stress (e.g. air pollution, traffic load and flow, noise) may be alleviated and thus improve quality of living. A vehicle sensor network alone has a drawback though. Dissemination of the sensor data is only possible when other cars are in communication range. If no car is in range, the data must be stored to be offloaded at a later time. The network becomes a delay tolerant network in which time between sensing the data and its dissemination can be considerable. During this period, the data can become stale and not valid anymore. The use of a fixed infrastructure to offload the data to—and to get the data from as well—will improve timeliness of data dissemination.

It is tempting to demonstrate the potential of infrastructure-assisted vehicular sensor networks and HexDD with an elaborate though realistic

Table 1. Overview of related works

Name of the work	Type	Goal
VANETs: infrastructure-less		
Persistence Broadcasting	Broadcasting	Broadcast suppression techniques
DV-CAST	Broadcasting	Directional broadcasting
SRD	Broadcasting	Directional broadcasting
ackPBSM	Broadcasting	Flooding
Kosch et al. (2006)	Broadcasting	Context-based flooding
OTHA	Broadcasting and Opportunistic sensing	Provide information of upcoming traffic
Abiding Geocast	Geocasting	Geocasting
GeoDTN+Nav	Unicast routing	Opportunistic geographical routing
VANETs: infrastructure-assisted		
DRR	Unicast routing	Multiple-path routing to meet services' reliability requirements
VPGR	Unicast routing	Context-based routing
MDH	Unicast routing and Geocasting	Data-harvesting to support applications' requirements, e.g., real-time
RAR	Unicast routing	Routing with reduced overhead by relying on a wired backbone network
DP and DP-IB	Geocasting	Dissemination to an area of interest
MCDD	Infrastructure deployment	Optimization of the placement of dead drops in road intersections
Festag et al. (2008)	Architecture	Connect roadside units to wireless sensor networks to reduce deployment costs
CGP	Architecture and data aggregation	Obtain an overview about road conditions in a certain geographical area
BusNet	Opportunistic sensing	Road surface monitoring
Pothole Patrol	Opportunistic sensing	Road surface monitoring

scenario taken from one of the application areas mentioned in the previous section. However, for the sake of clarity we will constrain ourselves in the following to a simple scenario where one vehicle provides data and another vehicle requests data.

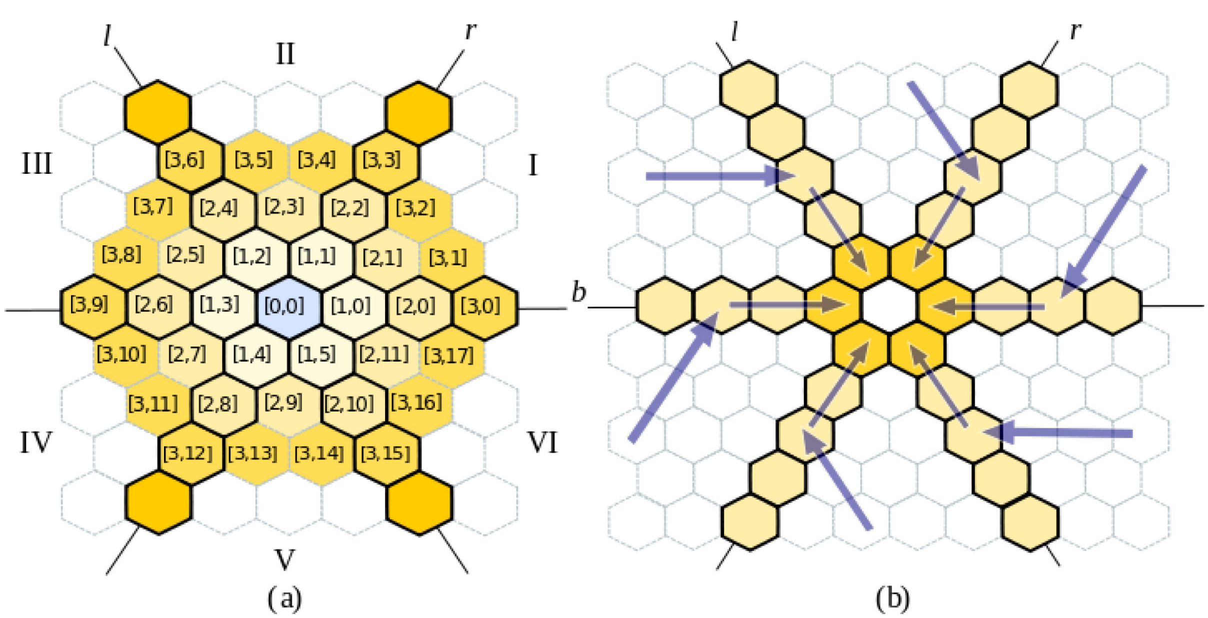
THE INFRASTRUCTURE NETWORK WITH ROADSIDE UNITS

The vehicular sensor network that we consider is a hybrid between vehicular networks and WSNs. The network consists of static and mobile nodes. The static nodes are sensors located along the roads, attached to existing traffic signposts and other infrastructure, such as traffic lights, bus and tram stops, parking meters, railway stations, and buffer stops. Locating sensor nodes on this kind of road infrastructure will often result in a network that is not enough dense or not evenly distributed over a city. Figure 2 shows the existing infrastructure nodes, the blue triangles, in the same city area shown in Figure 1. The distribution of these nodes is not uniform over the whole area. It is dense in some parts of the city, and sparse in some others, creating also disconnected parts in the network. Additionally, we propose to deploy sensors on lampposts, assuming they are regularly positioned along roads in the city, e.g. every 100 meters. These nodes embedded on Roadside Units (RSUs) serve as sensor and relay nodes. The network formed by them gives a complete coverage of the city area. The static nodes may be powered or able to perform energy harvesting, e.g. from sun light, thus not depending only on battery power. Vehicles moving in the city are the mobile nodes in the network. They send the information collected by their possibly many sensors to the static nodes in the network. They also ask for information from the network. Vehicles may also serve as relay nodes, passing messages from one node to another in the network, but this is more a supporting role in case holes are created in the infrastructure network.

In this work, we propose to create a virtual regular tessellation over the network area. Cells of this regular tessellation are hexagons, whose size is calculated based on the communication range of the VSN nodes. The cell size is such that any node in a cell can communicate with every node in an adjacent cell. In Figure 1 is shown the centre of the city of Enschede, the Netherlands overlaid with a hexagonal tessellation assuming a communication range of 250m for RSUs. Figure 2 shows the hexagonal tessellation for the same city area, where the light blue cells show the coverage that the exiting infrastructure nodes create for the virtual tessellation. The addition of the intelligent lampposts (iLPs) as RSUs ensures network connectivity and an acceptable sensor density, i.e. at least one sensor node per hexagonal cell. The yellow cells in Figure 2 show the virtual infrastructure defined by our protocol. This consists of three main diagonals of the tessellation and the n-hop ring around a centre cell (here the 3d-hop ring).

The virtual infrastructure is used by the data dissemination protocol for storing information produced by sensors in the network, e.g. detected events. Requests from vehicles are also sent to this infrastructure, making it a crucial element for the information exchange in the network. The virtual infrastructure is thus serving as a backbone for the communication. In a network where a major load of data and queries is coming from vehicles in the roads, it is reasonable to position the communication backbone in the major roads. These major roads have a strategic position for the transportation network, with most of the vehicles passing through them. The layout of our virtual infrastructure shows a strong similarity with the

Figure 3. Cell addressing in honeycomb tessellation and message data flow



city street layout. This resemblance allows us to use the real road infrastructure as the communication backbone in our protocol. The approach presented in this chapter is built on the premise that there is a close fit between the street layout and the virtual infrastructure. When a main road deviates from our virtual infrastructure, we use roadside units that are within the virtual infrastructure instead of main road RSUs.

HEXAGONAL TESSELLATION FOR DATA DISSEMINATION IN VSN

Near real-time applications require a fast delivery of information, and for many of these applications, e.g. those related to safety, reliability of event data dissemination is an important concern. In this chapter, we propose a data dissemination protocol based on hexagonal tessellation for a V2I communication. Hexagonal tessellation, which is often used to model cellular networks, refers to a tessellation of the geographical area into hexagonal cells. It is important to point out that in our proposal we do not use the concept of cellular networks. In cellular networks, a land area is divided into hexagonal cells having a base station located in the middle to provide non-overlapping service to the entire network. Cellular networks use hexagonal cells to provide radio coverage over a wide geographic area and allow an efficient channel allocation. In our proposal, we do not assume a cluster head (i.e. data collector) at the middle of a cell. Here, we use hexagonal cells to reduce the position precision to what is needed for the geographical communication. In our approach, we use these addressable units for the purpose of geographical routing.

In this chapter, we focus on geographical (i.e. position-based) routing for the case of vehicular sensor networks in a city environment. Geographical routing is beneficial since no global route from source node to destination node need to be created and maintained. Two nodes (i.e. vehicles or RSUs) can communicate when they are within a distance *R* of each other, called the communicable distance. Through periodic interactions (hello packets), a node can learn the location and cell of its neighbors. The data and query packets are sent without any map knowledge to the next hop neighbor, which is determined by our data dissemination protocol. In the rest of this section, we explain the creation of the hexagonal tessellation and its infrastructure followed by the hexagonal cell-based data dissemination, HexDD.

Construction of Virtual Infrastructure with Hexagonal Tessellation

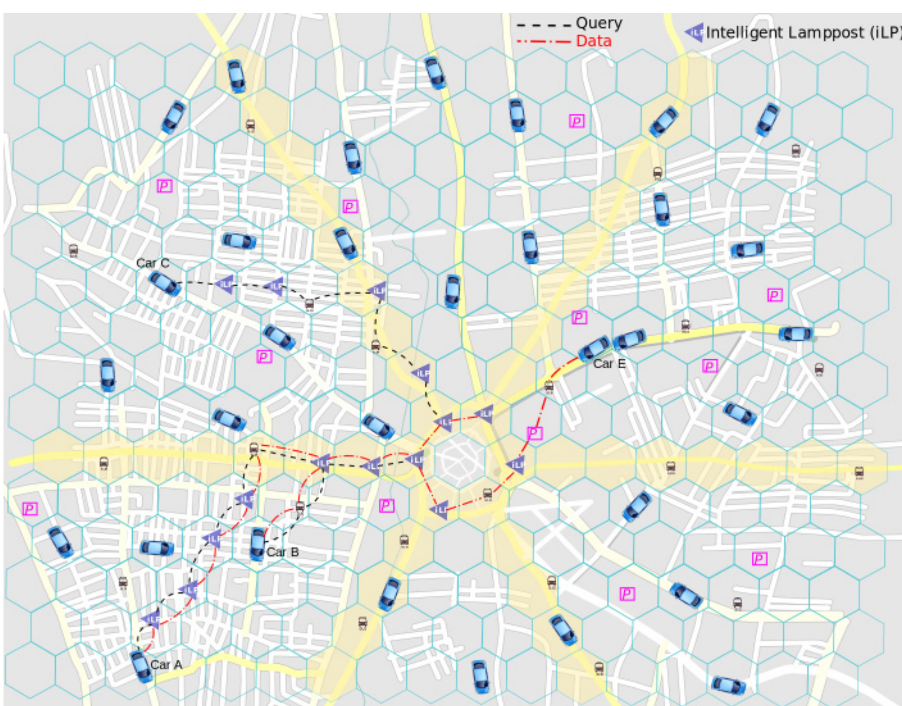
Hexagonal tessellation construction is, which is done at the network setup phase, is the initial step of our proposal. A honeycomb tessellation is completely determined by one reference hexagon because, once one hexagon is known, the remaining hexagons can be easily positioned. As shown in Figure 4, if the center hexagon is fixed at the center of the city, the whole network is fixed. In the following discussion, we assume the network has a fixed cell size, *r*, and network orientation. A network with a fixed cell size and network orientation is solely determined by the position of one reference cell. In our previous works (Tuysuz-Erman, Dilo, & Havinga, 2010; Tuysuz-Erman & Havinga, 2010), it is shown how a node associates itself with a hexagonal cell where it is located in. For node-cell association, a node needs to know the edge length of the hexagon, *r*, and the center of the city. In order for all nodes in two adjacent cells to be able to communicate with each other, the longest distance between two adjacent cells, $l = \sqrt{13}r$ must satisfy $l = \sqrt{13}r \leq R$, where R is the transmission range. Therefore, we choose the edge length of the hexagon, $r_{max} = R / \sqrt{13}$, such that sensors in adjacent cells are within communicable distance of each other. To let the other far infrastructure nodes know the center of the city, a static node deployed at the center of the city can broadcast its location over the city once at the network setup phase. All the RSUs receiving this information in the city can easily associate themselves with the hexagonal cell where they are located. When a vehicle starts to move in the city or enters into a new city, it asks the network settings (i.e. cell edge size, location of the center) of this city to the nearest RSU. After getting the settings, it will be able to calculate its cell address.

The hexagonal tessellation creates a circular structure on the city, starting from the center, and spreading with hexagonal rings to the end of the city. We use a kind of polar coordinate system to address the cells of the tessellation. Figure 3 shows the cell addressing used in hexagonal tessellation. We assign addresses of the form *[H, I]* to each sensor in the same cell, where H is the shortest cell-count of the node from the origin cell and I denotes the index of the hop-H hexagonal cell. The index starts at the right side of line b in Figure 3(a) and increases in the counter-clockwise direction. Hence, the nodes in the first-hop cells are addressed as [1, 0], [1, 1],..., [1, 5]. Observe that nodes of the form *[H,.]* are all located on the same hexagonal ring at distance H form the center cell. Since the number of cells on H^{th} hop hexagonal ring is $6\times H$, the cell addresses range from $[H, 0]$ to $[H, 6H-1]$. This addressing scheme serves as a positioning (coordinate) system that is rougher than the coordinates of the wireless nodes, with a precision appropriate for transmission range. Wireless nodes are associated with cell 'coordinates' based on their locations. The geographical routing that HexDD performs is based on cell addresses.

In hexagonal tessellation, we classify the wireless nodes into three groups:

1. Border nodes,
2. Ring nodes, and

Figure 4. Hexagonal tessellation overlaid on city area (assuming g =1) and data-query dissemination



3. Regular nodes, according to their position on the hexagonal tessellation.

The ring cells are selected according to the position of the most inner ring of the city. If the inner ring road of the city is covered by the hexagonal ring, *g*, then every node on ring *g* becomes a 'ring node.' In Figure 3(b), dark yellow cells are the ring cells assuming $g = 1$. The cells addressed as $[H, I]$ are 'border cells' if $I = (k - 1)xH$, where $H > g$ and $k \in \{1, ...,6\}$. The nodes associated with border cells, which are shown by yellow cells in Figure 3(b), are called 'border nodes.' The virtual tessellation is partitioned from border cells into different parts, called city zones, which are the white regions in Figure 3(b). All the other nodes located in city zones are called 'regular nodes.'

The virtual tessellation is partitioned from the main road-lines running through the city center into different parts (i.e. city zones) as shown in Figure 4. These main lines (yellow lines in Figure 4) together with a hexagonal ring (the most inner ring in a city) constitute the infrastructure for our protocol. They serve as a storage place for data and a meeting point for data and queries coming from cars moving in the city.

Lines *l*, *r*, and *s* are called as "diagonal lines" and half of these lines are called "border lines." A city is indeed split into zones with these borderlines. Each borderline caches information coming from the representative zone according to the forwarding directions shown in Figure 3(b). Finally, the central ring caches the information coming from all city zones.

Hexagonal Cell-Based Data Dissemination

In the context of vehicular sensor networks, the network we envision consists of vehicles and wireless nodes located on the fixed infrastructure on the roadside. Vehicles are the mobile sources (see Car E in Figure 4), reporting information from collected or processed data from their possibly many sensors. They are at the same time the mobile destinations (see Car A in Figure 4), asking information that the driver/owner considers important. Wireless nodes embedded on roadside units (iLP, parking places [P], and bus stops in Figure 4) serve as sensor and relay nodes.

In the rest of this section, we explain the main features of our data dissemination protocol: (1) data and query forwarding between sources, destinations and border/ring nodes, (2) Fault tolerance mechanism, and, (3) Mobility Management.

(Event) Data and Query Forwarding

Data and queries coming from each part of the city are sent to one of the main roads (i.e. borderline) bordering it, according to the predefined directions shown in Figure 3(b). The data is then sent towards the central ring, which has therefore knowledge about the whole city. The data is cached on every cell of the central ring. In our data dissemination protocol, we assume a pull based approach, which is a form of request and response model. In pull based data dissemination, any vehicle is enabled to query information about a specific type and/or location. Once a query is issued from a car (Car A and C in Figure 4), it is sent to the main road assigned to the part of the city where the car is. The query is sent along the main line towards the central ring to search for the required data. When the data is found, it is sent to the car that issued the query. While the data is being forwarded towards a destination node along the border cells, border nodes receiving data also cache it. If the data is already in that main line (assume Car B sends a query after Car A gets the data from central ring), it is sent back to the car without its query is being forwarded to the central ring. The HexDD protocol performs this routing of data and query messages by exploiting the road infrastructure as a communication infrastructure. The strategic position of the road infrastructure allows for fast communication routes, assuring fast response and at the same time efficient data dissemination.

The following algorithm shows how a node finds the next hop cell based on cell addressing used in hexagonal tessellation. In the first part, it calculates the next hop cell of a node in one of the city zones towards the central ring via border cells. This part is used for data and query dissemination towards the central ring. The second part shows the calculation of the opposite path from central ring towards a cell in one of the city zones via border cells.

Algorithm 1: Hexagonal Cell-Based Data Dissemination

- Input
  - $[H, I]$, address of the current cell
  - $[H_s, I_s]$, address of the destination vehicle's current cell
  - g, H of the central ring
- Output
  - $[H, I]$, address of the next hop cell
- Find next hop cell towards central ring
  - $k = \lceil I \,/\, H \rceil$
  - *If* $H < g$ then
  - $[H, I] \Leftarrow [H-1, I-1]$
  - *else if* $H == g$ *then*
  - *Circulate packet in the ring*
  - *end if*
- Find next hop cell towards destination vehicle
  - $k = \lceil I_s \,/\, H_s \rceil$
  - $H \Leftarrow H + 1$
  - *If* $H \leq kH_s - I_s$ *then*
  - $I \Leftarrow I + k - 1$ *// in the border line*
  - *else*
  - $I \Leftarrow I + k$ *// within a city zone*
  - *end if*

Fault Tolerance

The proposed data dissemination protocol assumes that there is at least one node (preferably a RSU) which performs multi-hop routing within each cell. However, this may not be always the case. Some nodes may be temporarily unavailable. Therefore, holes are created where there is a group of cells that do not have any active RSU inside. To handle this problem, we propose a hole detection and bypassing mechanism, which is an important feature that shows how to maintain the honeycomb tessellation even if a part of the infrastructure is missing.

A vehicle or RSU can easily detect the hole region by checking its neighbor table, which is updated by periodic beacon packets. If the node has no neighbor on the next 2-hop cells in its transmission range, it concludes that there is a hole at that part of the city. We can divide hole bypassing mechanism into two parts:

1. **Route recovery when sending packets (data or query) from a vehicle on a city zone towards the central ring:** To find an alternative path, the node, which wants to forward its packet towards the central ring, checks its neighbors and chooses the neighbor having the smallest *H*. By sending the packet to the neighbor node having the smallest *H*, the node tries to get as much as close to the central ring. Having a smaller *H* than the others means that this node has a smaller hop count to the central ring.
2. **Route recovery when sending data packets from the central ring towards a destination vehicle on a city zone:** The easiest ways to establish the path from the central ring to a destination vehicle moving on a city zone is storing the reverse path in the query. Since sink sends a new query whenever it changes its cell, it is an efficient approach. The reverse path in the query packet recovers the holes at the path back to the sink because when the query is being sent towards the central ring, the alternative path is calculated and stored in the query. It is also possible to calculate

the reverse path from the cell address of the destination vehicle.

Algorithm 2 gives the details of HexDD with route recovery. For simplicity, we only give the details of route recovery when sending packets from a vehicle on a city zone towards the central ring. The opposite path recovery uses a similar approach to calculate the next hop to recover holes. Figure 5 illustrates the fault tolerance mechanism in HexDD.

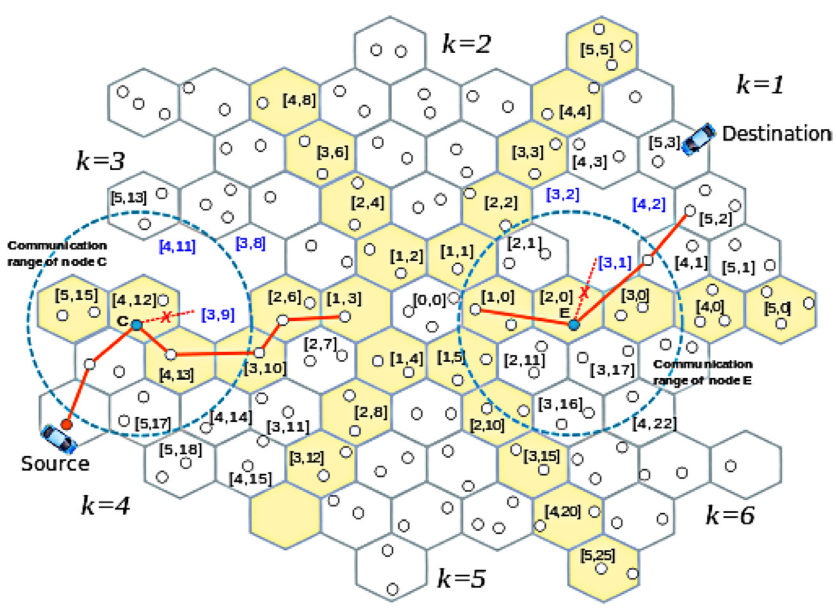
Algorithm 2: Hexagonal cell-based data dissemination with route recovery

- Input
  - $[H, I]$, address of the current cell
  - g, H of the central ring
  - $N = \{n_1, ..., n_m\}$, list of neighbors
  - $N_a = \{[H_1, I_1], ..., [H_m, I_m]\}$, list of cell addresses of neighbors, where node n_m is in cell $[H_m, I_m]$
- Output
  - *n,* next hop neighbor to forward packet
- Find next hop neighbor towards central ring
  - $[H_c, I_c] \Leftarrow$ *find next hop cell towards central ring (Algorithm 1.I)*
  - *If* $[H_c, I_c] == [H_i, I_i] \in N_a$ then
  - $n \Leftarrow n_i$ *// forward data to a neighbor in the next cell*
  - *else // there is a hole, enter route recovery*
  - $n \Leftarrow n_j$ *with* H_j the smallest H in N_a where $j \leq g$
  - *end if*

Mobility Management

In the motivating VANET scenario, both the source and destination vehicles are mobile entities of the network. The impact of destination and source mobility on the dissemination scheme is very small because when destination or source

Figure 5. Route recovery mechanism in HexDD



vehicle moves to another cell, it only changes its connection point to the static infrastructure. When a source vehicle moves to another cell, it sends its data to the nearest RSU to become connected to the infrastructure. When destination vehicles move between cells, they need to send a new query message towards the central ring to inform the ring nodes about their new cells. If there is no direct communication exists between a destination/source node and a RSU, another vehicle in the next hop cell can be used as next hop until reaching a RSU. Another option is that the packet is carried by the destination/source vehicle until it could be forwarded to a node which will be a RSU if any exits in the communication range or a vehicle. This ‘carry and forward’ concept (Zhao & Cao, 2008) can be easily combined with our geographic forwarding protocol, HexDD.

PERFORMANCE EVALUATION

In order to evaluate the performance of our data dissemination protocol described above, we used the open source network simulator NS-2 (McCanne, Floyd, Fall, & Varadhan, 1997) version 2.33 as it is widely used for research in vehicular ad hoc networks. We have added a new data dissemination agent (i.e. HexDD) into NS-2 over the currently implemented network stack and added our logic as a routing agent.

In the following, we provide first a description of the simulation environment and scenarios characteristics and then present the evaluation methodology, the metrics for comparing the protocols. Finally, we analyze the simulation results we obtained.

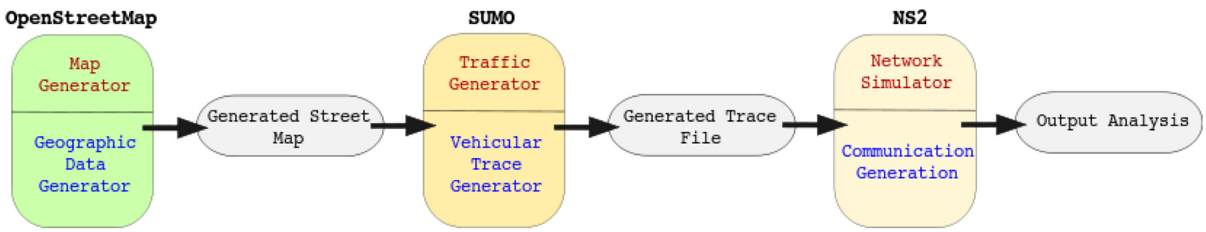
Simulation Environment

In our VANET simulation we use three main components: a network component, capable of simulating the behavior of a wireless network, a vehicular traffic component, able to provide an accurate mobility model for the nodes of a VANET, and a map component, capable of creating and providing free geographic data such as street maps. The vehicular mobility and wireless network models are incorporated in different simulation tools. SUMO – Simulation of Urban MObility (Krajzewicz, Hertkorn, Rössel, & Wagner, 2002) implements complex validated vehicular traffic mobility models. It is used for simulating a traffic scenario and generating an output file with vehicular mobility traces. The trace generated by SUMO is a mobility log for vehicles moving based on traffic regulations. It is possible to import different maps to SUMO to generate different test cases. Realistic urban areas (i.e. Enschede, the Netherlands) extracted from actual street maps are imported to SUMO. These maps are extracted from free maps available in OpenStreetMap (Haklay & Weber, 2008). After generation of mobility traces, they are fed into the network simulator, NS-2, as mobility scenario. In addition, static road infrastructure points, e.g. traffic lights, transportation points, and parking meters, obtained from OpenStreetMap are used as Road Side infrastructure Units (RSUs) in NS-2. We also generated iLP nodes in NS-2. The simulation is performed by NS-2 to obtain the final simulation results with the given inputs. Figure 6 shows the general view of the simulation environment.

Scenario Characteristics

In this chapter, we consider an urban area of 3500x4000m^2 that is the downtown and residential area of the city Enschede in the Netherlands. Vehicles are able to move freely on the urban graph respecting roads and intersection rules, more specifically, speed limitations and stops. Vehicles are able to communicate with each other using the IEEE 802.11 DCF MAC layer (Chen, Jiang, Taliwal, & Delgrossi, 2006). The radio transmission range has been deliberately over-evaluated and set to 250m for VANETs as we wanted to avoid biased performance evaluations

Figure 6. Simulation environment



due to disconnected networks. The simulation parameters are given in Table 2.

Evaluation Methodology

We compare the performance of the HexDD protocol with representatives from two main classes of ad hoc routing protocols:

1. AODV (Perkins, Belding-Royer, & Das, 2003), which is a MANET reactive routing protocol,
2. GPSR (Karp & Kung, 2000), which is a MANET geographical routing protocol.

Since only a limited work has been done on infrastructure-assisted data dissemination for vehicular sensor networks inside the city environment, we have chosen two MANET protocols for comparison. Although the operations of VANET and MANET are the same, due to the difference in high-speed mobility of vehicles, VANET communication requires suitable modification in the predefined routing protocols. Some efforts on improving classical MANET routing protocols to operate efficiently in VANET can be found in Abedi, Fathy, and Taghiloo (2008) and Wu, Wang, and Lee (2010). Since we have no intention of coding these improvements in NS-2 from scratch due to time constraints, we use AODV and GPSR implementations in NS-2.33. These protocols are served as the benchmark to judge the performance of our proposed HexDD.

HexDD, AODV, and GPSR protocols are based on only local knowledge (i.e. one-hop neighbors). Vehicles do not use any global knowledge such as a digital map of the region to forward their data packets (Lochert, et al., 2003). In HexDD, AODV, and GPSR, we make use of periodic "hello" messages to get information from the one-hop neighbors of vehicles and RSUs.

Metrics

The performance of the routing protocols has been evaluated by varying the number of destination and source vehicles. We have measured several significant metrics for data dissemination in VSNs:

- **Packet Delivery Ratio to Destinations (PDR_D):** It is the ratio between the number of data packets successfully delivered

Table 2. NS2 simulation parameters

Simulation time	300s
Simulation Area	3500x4000m^2
Transmission Range	250m
Number of RSUs	800
Number of vehicles	300
Vehicle mobility	v_{min}=0km/h, v_{max}=100km/h
Source/Destination selection	Random
Number of source vehicles	1, 5, 10, 15, 20
Number of destination vehicles	10, 20, 30, 40, 50
MAC Protocol	IEEE 802.11 DFC
Hello Interval	1s
Data Interval	1s

at destination vehicles and the number of data requests (i.e. queries) sent by the destination vehicles.

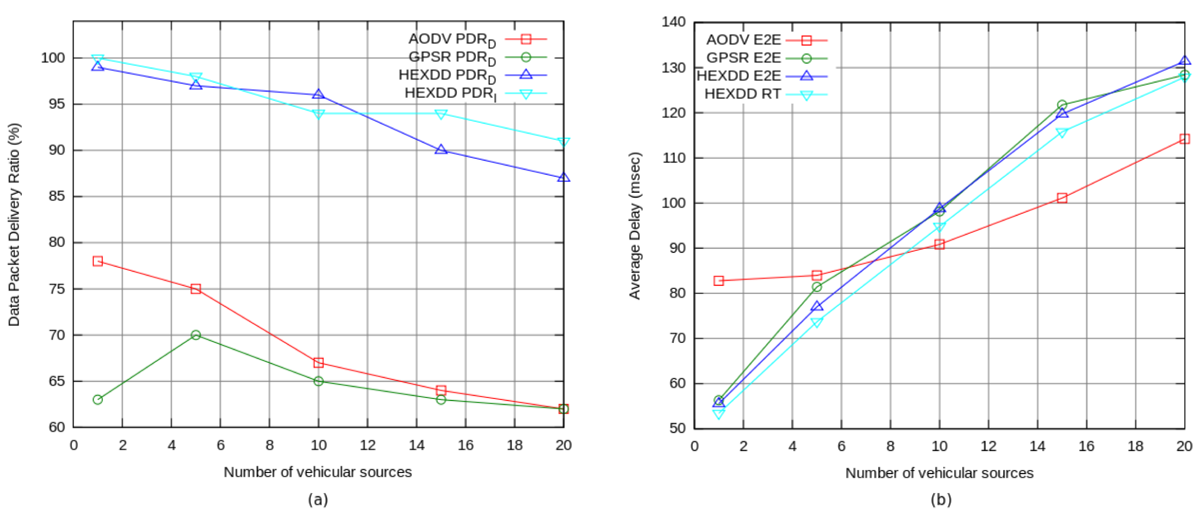
- **Packet Delivery Ratio to Infrastructure (PDR_I):** It is the ratio between the number of data packets successfully delivered at the infrastructure and the number of data packets sent by the source vehicles. The average packet delivery ratios *(PDR_D)* and *(PDR_I)* show together the ability of the routing protocol to successfully transfer data on an end-to-end basis.
- **End-to-End Delay (E2E):** It measures the average end-to-end transmission delay by taking into account only the successfully received packets. The average delay characterizes the latency that the routing approach generated.
- **Response Time (RT):** It is the average time between sending the request and getting the data for each vehicle.

Simulation Results

Impact of Number of Source Vehicles

In this set of simulations, we have 30 randomly selected destination vehicles in the VANET. The graph, shown in Figure 7(a), demonstrates the good performance of the proposed HexDD in terms of higher PDR_D, compared to the other two protocols, and that is for varying number of vehicular sources in the VANET. This is an expected result of using roadside network for vehicular communication. The graph indicates that regardless of the underlying protocol, PDR_D generally tends to decrease along with increase in the number of sources. Indeed, when the number of sources increases, the packet drops subsequently increase. Since only HexDD proposes a virtual infrastructure in VANET, we have calculated PDR_I only for HexDD in the simualtions. The data packet delivery ratio to infrastructure is also very high in HexDD protocol. Results prove that the use of RSUs and virtual infrastructure in order to cache the data coming from different sources improves the performance of data dissemination in terms of data delivery ratio. Figure 7(b) shows end to

Figure 7. Performance of three protocols in terms of (a) data packet delivery and (b) average delay for different numbers of vehicular sources



end delay for three protocols and response time for HexDD. Since we use a pull-based approach in HexDD, we have also defined and measured RT, which is the time elapsed between when a destination vehicle sends a query and when it receives the data coming from the central ring. As show in the Figure 7(b), RT of HexDD is smaller than E2E delay of the HexDD. The E2E delay of HexDD and GPSR are very close to each other. The E2E delay of AODV is the smallest when we have 10 or more sources in the network. The AODV protocol is able to keep the average delay of the transmitted packet in an implicit control by dropping packets for which it does not have a route.

Impact of Number of Destination Vehicles

Figure 8 shows the comparison of three protocols in terms of data delivery ratio and average delay for varying number of destinations when we have 20 randomly selected vehicular sources in the VANET. In Figure 8(a), when there are 10 sources in the network, PDR_D and PDR_I of HexDD are very close to 100%. Both PDR_D and PDR_I of HexDD decrease when we increase the number of destinations. However, decrease in PDR_D of HexDD is bigger than decrease in PDR_I of HexDD. On the other hand, AODV and GPSR show the most drastic drops in their delivery ratios, with a 20-24% decrease from the 10 destinations simulation to the 50 destinations simulation. Figure 8(b) plots the average data delivery delay for all protocols and also response time for HexDD. E2E delay of AODV is less sensitive to the added destinations than the other protocols. Since GPSR and HexDD are based on geographic routing, their E2E delays are close to each other. Both have route recovery phases when a packet reaches to a dead end. The planar graph traversal strategy of GPSR can not always guarantee to recover the route to the destination; therefore, its data delivery ratio is much smaller than HexDD. However, although the data delivery ratio of GPSR is much smaller than HexDD, its E2E delay for successfully received packets at destination vehicles is close to HexDD. This is due to the fact that the route recovery strategy of GPSR also results in longer paths than recovery strategy of HexDD.

FUTURE RESEARCH DIRECTIONS

The protocol we propose takes care only of the routing of messages, leaving aside related topics like data aggregation through the route, neither any kind of data processing. The communication infrastructure that we use takes over the storing of network data. This makes it a good candidate where information processing can take place. This could be supported by deploying powerful RSU nodes in the infrastructure.

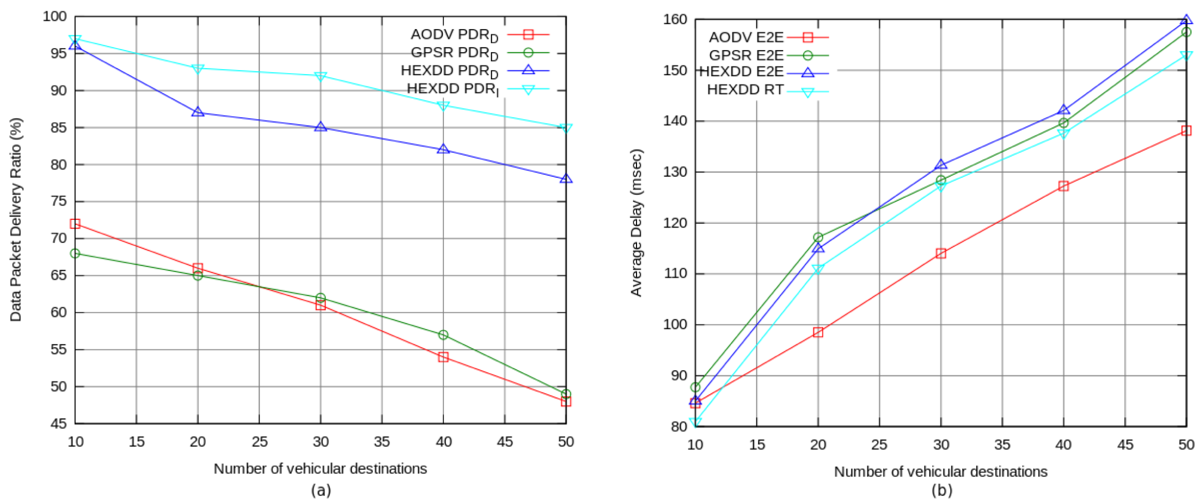
The HexDD protocol does not put attention on the kind of information that is flown in the network. Indeed, different sensors can be deployed on roadside units and many others are available on cars. This richness of data collected by the different sensors need to be properly handled, in terms of storage, intelligent processing, and transmission.

In this work, we did not put much attention to the fitting of virtual infrastructure with the read road infrastructure. A best fit can be reached via transformation of the tessellation, e.g. rotation, directional scaling, etc. Such transformation would require an adaptation of the addressing scheme, i.e. the association of a node with the virtual hexagonal cell. The routing of messages remains the same, requiring no changes.

CONCLUSION

In this chapter, we proposed a data dissemination protocol for VSNs. The network we envision consists of vehicles and roadside units. The RSUs are the lampposts equipped with small transceivers and sensors, positioned along roads at roughly equal distances, in addition to the existing com-

Figure 8. Performance of three protocols in terms of (a) data packet delivery and (b) average delay for different numbers of vehicular destinations



munication and traffic control infrastructure. This fixed network is inexpensive, and it provides a full and stable coverage of a city area. This VSN has advantages compared to a vehicular network whose coverage depends on the traffic situation and is usually unevenly distributed over a city.

The proposed data dissemination protocol, HexDD, is built upon a virtual tessellation of the city area. The cell size of a hexagon is such that any two nodes in adjacent cells can communicate with each other. The hexagonal tessellation creates a circular structure on the city, starting from the centre, and spreading with hexagonal rings to the end of the city. The main diagonals of the hexagonal tessellation together with a hexagonal ring constitute the infrastructure for our protocol. We use a kind of polar coordinate system to address the cells of the tessellation. This addressing scheme serves as a positioning (coordinate) system that is rougher than the coordinates of the wireless nodes, with a precision appropriate for the transition range. Wireless nodes are associated with cell ’coordinates’ based on their location. The geographical routing that HexDD performs is based on cell addresses.

This virtual infrastructure fits with main radial roads of the inner ring of a city that become the communication backbone for the protocol. They serve as a storage place for data and queries coming from cars moving in the city. Data and queries coming from each part of the city are sent to one of the main roads bordering it. The data is then sent towards the central ring, which has therefore knowledge about the whole city. Using main radial roads and the inner ring as rendezvous areas for data and queries, and employing roadside network for vehicular communication help to improve data delivery ratio while providing fast response in VANETs as shown in the simulations. The protocol can serve many applications of a VSN, such as traffic monitoring and control, environmental monitoring, and safety warning.

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