An Approach for the Integration of Smart Antennas in the Design and Simulation of Vehicular Ad-Hoc Networks

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Abstract**—The radio channel is a limiting resource in vehicular ad-hoc networks. A lot of possible applications in the field of vehicle-to-vehicle and vehicle-to-infrastructure communication will make use of sending messages to destination nodes addressed by geographical coordinates. Beam forming, which is the transmission of a message's signal explicitly into a specific spatial area by exploiting a phase-delayed array of antennas, can be seen as an approach to reduce the overall channel load in vehicular ad-hoc networks. Due to the implementation of today's network simulators, the analysis of the advantages and possible drawbacks of beam forming on vehicular ad-hoc network scenarios is hardly possible. In this paper we show a way in which a simulation framework typically used for research on vehicular ad-hoc networks can be extended by a realistic channel simulation and a physical layer simulation which allows studying the beam forming abilities of a smart antenna system.**

I. INTRODUCTION

Inter-vehicle communication has been seen as one future approach to reduce the amount as well as the impacts of accidents on our roads. Typically possible applications based on an inter-vehicle communication platform are giving vehicles the ability to propagate warning messages like information about dangerous street conditions, for example suddenly appearing ice or oil, to other vehicles. At the same time an extension of a driver's range of sight would be thinkable. This can be interesting, for example, at badly visible intersections or at hidden ends of traffic jams.

One approach to implement vehicle-to-vehicle communication is wireless ad-hoc networks. Applied to vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, the concept of ad-hoc networks is called vehicular ad-hoc networks (VANETs). While infrastructural nodes like road-side units can be used to extend the type and quality of applications, such components are not necessary for network organization purposes. Both, the network organization and the multi-hop transport of messages from a sender node to the destination node(s) are managed by the network nodes, i.e. the vehicles, themselves.

VANETs are quite a challenging field of research, which is due to several well-known reasons: The physical layer (PHY) is suffering from various physical effects of the radio channel, e.g. slow and fast signal fading and Doppler shifts caused by the nodes' mobility. The medium access control layer (MAC) has to provide a robust, fair and - depending on the application - even a time-constrained access to the radio channel which acts as a shared medium. At the same time, the MAC layer has to cope with packet collisions which occur from hidden or exposed stations. The network layer (NET), which is beyond other tasks responsible for routing messages through the network, has to find a suitable routing strategy for specific situations and requirements of applications. On the one hand, having too less nodes forwarding the messages that they have received will cause a possible loss of information in the network - vehicles might not reach each other. Configuring too many nodes in a way that they resend all of the received messages can easily lead to a too high channel load. As the radio channel is usually a limited resource in VANETs, a highly loaded channel will increase the probability of packet loss due to collisions or medium access timeouts.

A lot of studies have been done to analyze and optimize the behavior of the MAC or the NET layer, but typically, the most parts of research and optimization are limited to one layer only. In this paper, we will present a model and a concept for an implementation of a simulation framework which allows a cross-layer analysis of VANETs that combines the radio channel, the antennas and the physical layer with the network. We will show a way to integrate the concept of smart antennas with dynamic radiation patterns into an accurate simulation environment for VANETs. Accurate means that the VANET simulation is based on a radio channel simulation that considers the environment's effect on radio signal transmission.

The paper is structured as follows: In the next section, we will describe a communication scenario that we would like to take as an example to apply our method to and explain the problem statement which is taken as an example for this paper's study. After then, related work will be introduced. The next section presents basic information about VANET simulations, geocast routing and smart antennas. This will be followed by a presentation of our model which is then applied to an implementation of VANET simulation framework. We will close the paper with a section for conclusion and outlook.

II. PROBLEM STATEMENT

In VANETs, various imaginable applications produce different communication patterns. A lot of applications rely purely on cooperative awareness messages, i.e. beaconing messages which are sent out periodically by each vehicle which is equipped with an on-board unit. The vehicles in reachability distance learn about their neighboring vehicles and are able to use this information for example for an application that warns of cars that have been approaching at an intersection with a too high speed.

Other applications need to address specific nodes of the VANET directly, which often involves multi-hop routing of messages. Besides well-known addressing schemes like unicast, multicast and broadcast, one further type of addressing typically considered in VANET research is the so-called geocast message. Geocasts are addressed to network nodes residing in a geographical region at the time of transmission. The addresses used for geocasts can be coordinates of the Global Positioning System (GPS), for example. Safety or comfort applications based on V2V or V2I can be heavily depending on messages which have to be transmitted to specific geographical areas. For example, the warning message sent by a vehicle at the end of a traffic jam in a foggy or mountainous area is usually only relevant for vehicles that are approaching the traffic jam's end, but not for the vehicles which are already caught up in the traffic jam. Therefore a clear direction into which a message should be forwarded can be derived.

We expect that the idea of *beam forming* can be one instrument to improve the performance of applications in VANETs which are based on geocast messages. Beam forming is part of the concept of smart antennas. We use the term beam forming for an array of sending antennas with an adjustable radiation pattern. This is done by a phase-delayed feeding of the array elements. Depending on the phase-delay between the elements of the antenna array, the directivity changes, which means that the amount of signal power being transmitted into a specific spatial area can be controlled dynamically at runtime. This allows a distribution of signal power to places where it is actually needed while the radio channel utilization can be reduced at other positions.

III. RELATED WORK

As geocast messages play an important role in the idea of future VANET applications, they have already been a very intensive matter of research. The basic idea of geographical routing has already been proposed by Imieliński and Navas in 1996 [1], [2]. Algorithms for geocast routing were presented in 1999 [3]. The routing algorithms were later optimized for VANETs, for example in [4] and [5]. In [6] and [7] an overview about the state-of-the-art geocast routing strategies for VANETs is given.

In all of the introduced publications, the geocast is only considered as a service offered and realized by the network layer to the application. Assuming a multi-hop VANET scenario where a subset of all participating nodes share a common broadcast medium, the routing can be merely seen as having a network node to decide whether to resend a received packet or not. The physical layer, the antenna and radio channel are not considered explicitly in these publications. For wireless networks a simple pathloss model based on the distance between sender and receiver is assumed as proposed by Friis in [8]. The effects of obstacles (like vehicles and buildings) on the radio signals is neglected or approximated by an additional completely statistic fading term, while the real environmental situation is not taken into account. The antenna is typically modeled as an approximation of an isotropic antenna, which means that the directivity pattern of an antenna is neglected.

A lot of progress has been going on in digital signal processing for the last years. This allows to develop physical layer systems which are able to do highly sophisticated signal generation and analysis on even several antennas in parallel. This makes systems possible which rely on the general concept of *Multiple Input Multiple Output (MIMO)*, i.e. a communication system where both, sender and receiver, are equipped with more than one antenna [9]. One possible implementation of a multi-antenna system is beam forming by using a phased-delay feeding of an antenna array at the sender. The idea of beam forming itself is not new, either. Its roots are going back to military radar systems in 1944. Beam forming will be also part of the upcoming WLAN standard IEEE 802.11ac [10] and it has also been already proposed for the usage in VANETs by Stübing et al. [11]. While they discussed the advantages of beam forming for VANETs, they did not give information about linking beam forming models with a radio channel model to run realistic simulations.

IV. BACKGROUND INFORMATION

In this section, we give some technical background information that is needed to understand our approach.

A. Beam Forming Smart Antennas

A real antenna does not radiate the power into all directions of space equally. Depending on its geometry, the radiated power is focused towards specific radiation directions. A half-wave dipole, for example, radiates most of the power perpendicularly of itself, but almost no power can be received at the top or bottom of the dipole. This is depicted in Figure 1. The antenna gain is a function which depends on the angles of detection and on the geometry of the antenna. Evaluating the gain function for given angles, the plot of the resulting value table is called antenna pattern. This can be used to characterize the radiation behavior of an antenna.

Electromagnetic waves spread according to the principle of superposition. This means that the voltage which can be measured at the output of a reception antenna depends on a linear superposition of the electromagnetic field components at the time of measurement and at the reception antenna's

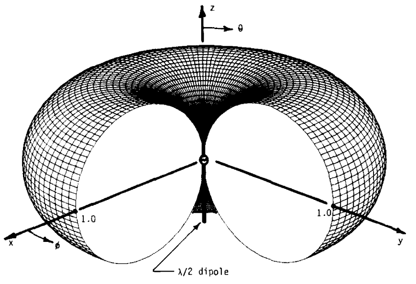


Fig. 1. **Angle-depending gain of a single $\frac{\lambda}{2}$ dipole antenna** (based on [12]).

position. As the electromagnetic field is a vector field, parts of the field can interfere in a constructive or destructive way. When neglecting any near-field effects (i.e. effects that can be measured within a distance of one wavelength from the sending antennas), two or more antennas can be used to generate constructive or destructive interferences for a requested angle. The angle can be modified without moving the position of antennas. Instead of this it is possible to change the directivity by inserting a phase-delay between the supply currents of the antennas. This leads to the possibility of having a variable radiation pattern by changing the phase-delay or the number of active sending antennas on demand. Combined with a PHY layer implementation which is capable to change the phase-delay dynamically, the modification of the radiation pattern can be done in software.

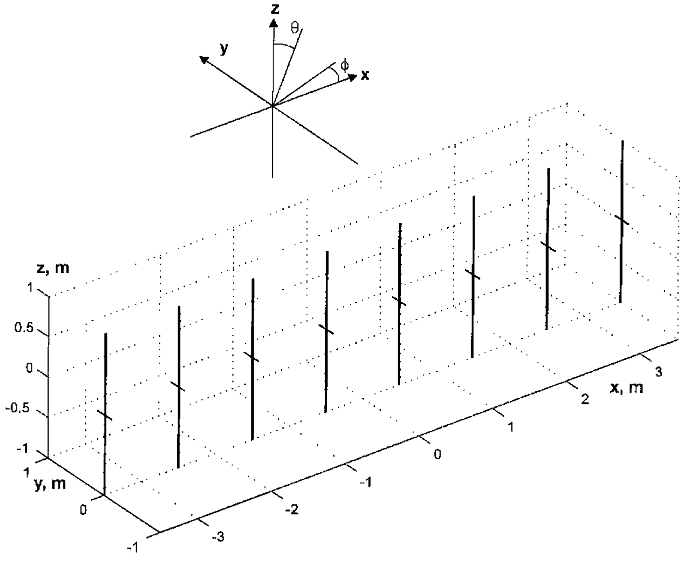
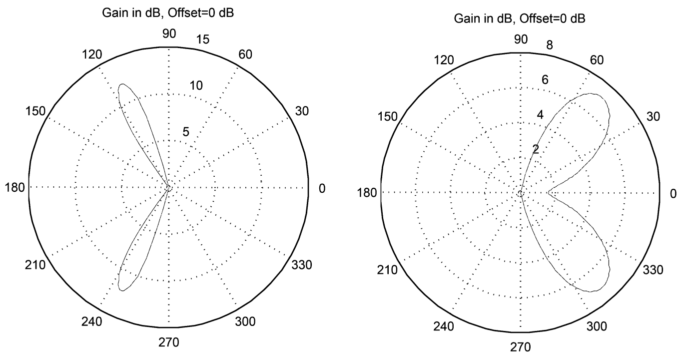


Fig. 2. **Exemplary alignment setup of linear array consisting of 8 dipole antennas** (based on [13]).

In Figure 2 a setup of a linear antenna array consisting of 8 dipole antennas is illustrated together with a sketch of the angular relations. In Figure 3 the radiation patterns of linear antenna arrays are depicted. Two conclusions, which are important for our approach, can be drawn:

- The higher the number of antennas, the narrower a radiation beam can be focused.
- Beam forming also introduces side lobes, i.e. the transmission power does not only leave the antenna array perfectly at the desired angle, but to other directions as well. This must be considered in VANET simulations because it can introduce unwanted side effects.



(a) (b)

Fig. 3. **Exemplary pattern of linear antenna array.** (a) shows the radiation pattern of a linear antenna array consisting of 13 half-wave dipoles with a distance of $\frac{\lambda}{3}$ configured for maximum radiation to $\phi = 115°$. (b) shows the pattern of a linear antenna array consisting of 5 half-wave dipoles with the same distance configured for maximum radiation to $\phi = 45°$.

B. VANET Simulations

The most widely used methods to study VANETs are network simulations. This is founded in mainly two reasons: Field tests of VANETs would require a large number of cars which have been equipped with prototypes of ad-hoc network communication devices. While field tests are more expensive than simulations, they lack at the same time flexibility at early stages of development. Another positive aspect of studying the behavior of such complex and distributed systems by using simulations is that simulations allow to investigate the direct influence of distinct parameters, i.e. the simulations deliver reproducible results. While keeping, for example, environmental parameters like the behavior of the radio channel or the distribution of the vehicles on the street constant, the influence of other parameters, like the algorithm used to route packets through the network, can be studied. An in-depth discussion of the advantages of simulations can be found in [14].

The simulation approaches typically consist of a discrete event-triggered network simulator where a mobility model for the characteristic movement of the simulated vehicles is added to. There are several simulation frameworks available to study VANETs. They are also actively used in research projects for routing and especially geocast routing strategies in VANETs. While considering geocast messages in multi-hop routing strategies is a very active topic of research, most of this work is limited to the network layer of the ISO/OSI communication model. With nowadays network simulation tools used in the design and evaluation step like NS-2 [15], NS-3 [16], JiST/SWANS [17] or OMNeT++ [18], the improvement which could possibly achieved by the usage of smart antennas in general or especially beam forming cannot be evaluated. The reasons are given in the following subsection.

C. Physical Layer, Antenna Model and Radio Channel Models in VANET Simulations

An in-depth look into network simulation frameworks which are typically used in VANET studies shows flaws especially at the lower layers of the simulated communication system:

- **The PHY-Layer is almost neglected.** The frameworks used for VANET simulations originate from tools that have been developed for the simulation of wired networks. In wired networks it can be sufficient to estimate the physical layer and the communication channel by using, for example, statistically described occurrences of bit errors or even by assuming an error-free line. A detailed simulation of signal processing is not necessary. This leads to the fact that the concepts and tools used for VANET research have a lot of shortcomings in the simulation of the physical layer. Typically, the signal generation and reception is not considered at all. The simulation part of the physical layer merely consists of adding additional bits used by the communication system, e.g. for the purpose of channel estimation and training sequences.
- **Very simplistic radio propagation models.** Besides this, the radio channel is typically considered with a very bad approximation of the behavior of a real system. For example, the signal's path-loss during its propagation on the radio channel is modeled only as a function of the distance between the sending and the receiving node extended by some statistical fading. Environmental effects, e.g. specular reflection of signal power at walls, diffuse reflection at trees, diffraction at edges, refraction while passing through different layers of materials while being partly absorbed, are neglected.
- **Non-existent or only partly-existent antenna models.** While some simulators assume just unrealistic isotropic antennas, some other ones come with very simple and static model of an omni-directional antenna [17]. A static antenna model neglects the fact that the antenna gain is dependent on the angle between the sending and receiving nodes. In spite of this well-known fact, the simulators just subtract a static antenna gain from the pathloss. This reduces the validity of VANET simulations even for non-smart antenna systems, especially when the sending and receiving nodes are not aligned exactly parallel which can occur in various scenarios, for example on uneven terrain.

These three facts depend on each other: When applying a realistic antenna model or beam forming antennas to a VANET simulation, a realistic radio channel consideration is strongly required. The reason therefore is that especially in non-line-of-sight conditions, which typically often occur in urban scenarios, it does not make any sense to simply consider the positions of sender and receiver nodes. Calculating angles between their antennas does not help in the case where parts of the signal are propagated indirectly. It is rather necessary to compute an antenna's directivity in relation to environmental surfaces which the electromagnetic waves interact with. Furthermore, a radio channel's influence on the signal cannot be processed in a VANET simulation that does not include any PHY layer simulation.

Therefore, we can conclude that to allow considering beam forming for geocast messages in VANET simulations, it is required to have a holistic model that handles the signal processing (i.e. the PHY layer), the smart antennas' behavior and the radio channel.

V. HOLISTIC MODEL FOR VANET SIMULATION

In this section, we describe how our approach has been developed. We initially started by taking a widespread discrete event-triggered network simulator as a base. We chose JiST/SWANS because of its good performance [19], but other simulation frameworks like OMNeT++ would have been also suitable in principle.

JiST/SWANS has been extended in various ways which is depicted in figure 4. The main extensions are described in the following subsections:

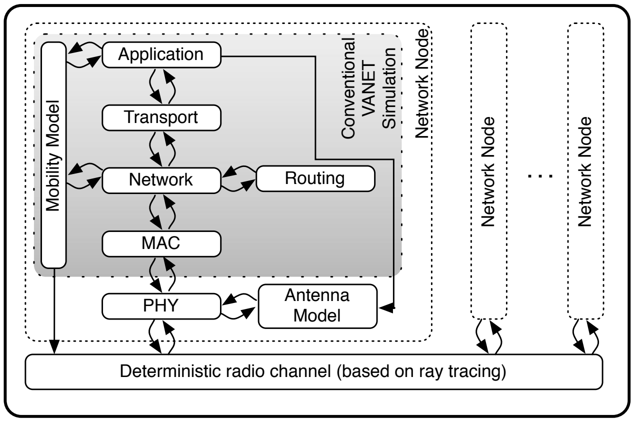


Fig. 4. **Extensions to the existing ad-hoc network simulator JiST/SWANS.** The parts highlighted in gray show which components are usually considered by VANET simulation frameworks like JiST/SWANS. The other parts have been added by us.

A. General Requirements

A classical network simulator for VANETs consists of two main parts: the communication model on the one hand and the mobility model on the other hand. While the communication model is responsible for the whole communication process of a network node, the task of the mobility model is to place and move the network nodes. Typically, a street random waypoint model is used [20] which gets a street map as an input, starts with a random distribution of the vehicles and then applies traffic models to simulate driving maneuvers.

As depicted in figure 4, various components of the network simulation depend on information from the mobility model. Due to this reason, it is extremely useful to work with input data that contains all necessary information in a consistent way. As well the application as the network layer have to get information about a node's position to communicate using geocasts. In our scenario, this information is also needed by the antenna model and the radio channel model. The channel model additionally needs information about obstacles that interact with the radio signal, for example buildings.

It is further necessary to have consistent coordinates for all described patterns in the input data and at all layers of the simulation framework, i.e. position information in the NET layer have to be the interpreted in the same way by the PHY layer.

B. MAC-/PHY Interface

The MAC layer is responsible for simulating the node's access to the shared medium. It is also used to generate frames according to the IEEE WLAN standard. We link the MAC layer which comes with the network simulation framework (JiST/SWANS) to a PHY layer which we implemented in Matlab/Simulink. For the sender, we feed the MAC layer's output as the input signal of the PHY layer. For the receiver, we feed the decoded output of the PHY layer is given to the MAC layer.

C. PHY Layer Implementation

The PHY layer for the IEEE 802.11p, which is proposed for the use in VANETs, has been implemented in Matlab/Simulink. Due to the model-driven approach it is quite easy to change or reconfigure specific parts of the model. The PHY layer consists of two parts: The sender part gets packetized binary data as an input and calculates a modulated base-band signal as an output. The second part is able to decode a received base-band signal and outputs the according binary data packets.

D. Antenna Model Implementation

We implemented a three-dimensional antenna model which is able to determine the angle-dependent antenna gain for a single omni-directional antenna, for a single user-defined antenna geometry and for a phase-delayed beam forming antenna array. As this paper has its focus on the latter, we describe the functioning of the antenna model by using the phase-delayed beam forming antenna array:

The antenna model gets an antenna configuration (form and position of the antennas) as an input. It further expects a designated direction as an input and then calculates an antenna pattern which describes the real-world behavior of an antenna which is driven in that way.

As the NET layer has already to handle geocast messages, it comes already with a routine that works on regional information. Therefore this information is already available in the NET layer. So in our implementation, the NET layer communicates via a control link with the antenna model to inform the antenna subsystem about a designated direction.

E. Radio Channel Simulation

The radio channel is simulated deterministically by using a three-dimensional ray tracing method as described in [21]. A much-improved version of this approach has been implemented. As the deterministic channel simulation consumes very much computation time, it is accelerated by the usage of modern general-purpose graphics processing units (GPGPUs) which can handle a lot of the necessary computations in parallel. The radio channel model gets a street and environmental map as an input.

In spite of all performance improvements, the deterministic radio channel simulation is still the most computationally intensive component. When a position of a sending node is given, the effort to calculate the channel's responses (pathloss and delay spread) for the whole map is not much higher than calculating the channel's response for a single receiver's position. Therefore we precalculate the radio channel behavior for the whole environmental map by dividing the map into a grid with an adjustable resolution. For all pairs of grid fields, we precalculate the pathloss and the delay spread. This is stored in a database which is exemplarily shown in table I.

The precalculation of the radio channel behavior introduces a problem when applying it to a dynamically configurable antenna directivity. This is due to the following reason: An antenna model is intrinsically applied when the ray tracer is executed to simulate the radio channel because the ray tracer has to consider sources and sinks of the power which is transmitted. This is not possible in our application, because at the point in time where the ray tracer precomputes the channel's behavior for the whole map, the network simulator has not been started. As the antenna pattern is no longer static, the ray tracer cannot consider it.

A possible solution to this problem is to assume an isotropic antenna by the ray tracer. Then, for each path that the ray tracer finds, we store the pair of outgoing angles ϕ_s and θ_s at the sender's antenna and the pair of incoming angles ϕ_r and θ_r at the receiver's antenna additionally in the database created by the ray tracer. During the run-time of the network simulation, the antenna model can weight the paths according to the actual antenna pattern by considering the paths' angles.

This approach allows to have a combination of a precomputed radio channel simulation (to improve performance) on the one hand and a dynamically adapting antenna pattern (which is required to simulate beam forming) at run-time on the other hand.

VI. CONCLUSION AND OUTLOOK

In this paper we described a simulation approach which allows studying a typical cross-layer aspect of VANETs: A smart antenna system in a VANET can be used to support the network layer in its task to forward geocast messages towards the requested destination region by avoiding unnecessary load to the radio channel. This is still work in progress. We just started to simulate small VANET scenarios to find out in how far beam forming affects the network's performance in different situations.

Position [m]						Angle [deg]					
Sender			Receiver			Sender		Receiver			
x	y	height	x	y	height	ϕ_s	θ_s	ϕ_r	θ_r	Pathloss [dB]	Delay [ms]
1281	1381	1.5	0000	1260	1.5	31	180	4	7	85.44	0.00086
1281	1381	1.5	0000	1260	1.5	30	180	8	12	44.23	0.00015
1281	1381	1.5	0000	1260	1.5	46	176	9	14	42.33	0.00013
1281	1381	1.5	0001	1260	1.5	49	174	9	16	62.85	0.00046
1281	1381	1.5	0001	1260	1.5	53	179	14	11	56.13	0.00039
1281	1381	1.5	0002	1260	1.5	57	170	15	9	75.54	0.00026

TABLE I
EXEMPLARY SIMULATION RESULTS OF DETERMINISTIC RADIO CHANNEL SIMULATION USING RAY TRACING.

In parallel we work on further improvements regarding the simulation performance. The simulation of the radio channel behavior is precomputed independently from the network simulation. Exploiting the GPGPU approach accelerated these precomputations tremendously. We are currently investigating if it is possible to use GPGPUs also for the PHY simulation which is the second-most computationally intensive part of the simulations following the radio channel simulation.

Evaluating beam forming is only one aspect of the paradigm cross-layer design which we have chosen as an example. Further approaches might be worth to be studied more closely in the future, for example the application of smart antenna arrays also at the receiver's side, other variants of MIMO systems like the spatial diversity as used in IEEE 802.11n or the implementation of a communication system for VANET which works in two independent frequency bands simultaneously – e.g. in 700 MHz and 5.9 GHz. In Japan, for example, these two spectra which are quite far apart from each other have been reserved for VANETs by the regulation authority. Using two frequency bands like these might be interesting to study the behavior of frequency-specific effects of the radio channel. A combination of two frequencies might offer the possibility to adapt to challenging channel conditions better.

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