Coupled vehicle and information flows: Message transport on a dynamic vehicle network

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Abstract

A freeway with vehicles transmitting traffic-related messages via short-range broadcasting is a technological example of coupled material and information flows in complex networks: information on traffic flows is propagated via a dynamically changing ad hoc network based on local interactions. As vehicle and information propagation occur on similar time scales, the network dynamics strongly influences message propagation, which is done by the movement of nodes (cars) and by hops between nearby nodes: two cars within the limited broadcast range establish a dynamic link. Using the cars of the other driving direction as relay stations, the weak connectivity within one driving direction when the density of equipped cars is small can be overcome. By analytical calculation and by microscopic simulation of freeway traffic with a given percentage of vehicles equipped for inter-vehicle communication, we investigate how the equipment level influences the efficiency and velocity of information propagation. By simulating the formation of a typical traffic jam, we show how the non-local information about bottlenecks and jam fronts can travel upstream and reach potential users.

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1. Introduction

The statistical physics of complex networks has shown to be a rapidly growing, inter-disciplinary research field. It has evolved from random-graph [1–3] and percolation theory [4,5] and been inspired by biological, technological and social networks [6–10], of which more and more data have become available in the last decades. A huge progress has been achieved not only in the description and understanding of these systems, but also in the mathematical theory itself [6]. Recent research focusses on the investigation of dynamical processes on networks or networks with a dynamically changing topology. Ad hoc networks of communicating cars include both aspects. And while it is straightforward to assume generally that the network structure affects the dynamics of information spreading on the network, in the case of inter-vehicle communication (IVC) the information flows on the network may also influence its topology, as traffic information influences the motion of the network nodes (the cars).

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In IVC, the network nodes are distributed in a metric space, and the topological neighborhood of each node is strongly correlated with its metric neighborhood because of the limited broadcast range. For a random spatial distribution of non-mobile nodes, Refs. [11–14] have investigated different network topologies generated by varying transmission power choices. The goal was to identify optimal global and distributed transmission power assignment strategies with respect to network connectivity and data throughput. However, in contrast to scenarios with fixed spatial positions of the network nodes, a freeway stretch with vehicles transmitting traffic-related messages via wireless technology is an example of a complex network with a real dynamic topology.

IVC is widely regarded as a promising concept for the transmission of traffic-related information. In contrast to classical communication channels, which operate with a centralized broadcast concept via radio or mobile-phone services, IVC is designed as a local service without central station and without the need for additional infrastructure. Vehicles equipped with a short-range wireless transmission device broadcast messages, which are received by all other equipped cars within the limited broadcast range. Commercial WLAN devices (wireless local-area network, IEEE 802.11 a/b/g) have already shown to be suitable for the transmission of messages between cars with a relative velocity up to 400 km/h.

Apart from the drivers appreciating reliable and up-to-date traffic information, the whole traffic system may benefit from IVC as well [15]. Adaptive cruise control (ACC) automates the braking and acceleration of a car. While the objectives of currently available ACC systems are to enhance the comfort and safety of driving, their impact on the capacity of the freeway is now moving into the focus of traffic research [15–17]. Transmission of traffic information via IVC could help ACC systems to recognize the traffic situation faster and more reliably. In addition, equipped ACC cars are able to detect very exactly the position of jam fronts and, thus, may spread such information. This could help ACC systems to increase road capacity by allowing them to drive with a driving strategy, that is well adapted to the current traffic situation. Since IVC will start with a small equipment level, it is crucial to investigate the functionality and the statistical properties of the message hopping processes under such conditions. Fast and reliable information spreading is a necessary precondition for a successful implementation of this technology.

In IVC, a dynamical process occurs on a network with a dynamic topology. Furthermore, when vehicles transmit traffic-related information, the dynamics of the nodes (cars) and the dynamics of message transport is mutually inter-dependent: the dynamically changing, spatial distribution of cars is the reason for message generation and also affects message propagation. The messages on the other hand can cause a change in the dynamics of the receiver cars, which is actually the intention of such a system. The complexity of this system is only restricted by spatial constraints, i.e., the networks nodes are distributed within a road network, moving along the links only in one of two possible directions. In the beginning of our analysis we will neglect the feedback mechanisms between the two dynamical processes for simplicity. Thus, it is possible to investigate some generic scenarios for the propagation of messages: cars detect their local traffic situation and generate messages, which have to travel upstream in order to be useful. For a low spatial density of cars equipped with IVC, the transport within one driving direction is obviously rather difficult or even impossible. Therefore, we propose to use cars of the other driving direction as relay stations for the upstream message transport, which guarantees connectivity at the cost of some time delay.

Our paper is organized as follows: in Section 2 we discuss the distribution of equipped cars on a freeway stretch. Then, we calculate in Section 3 the efficiency of message flows in the network of equipped cars. In Sections 4 and 5, we confirm our analytical results by microscopic traffic simulations and present an example, where jam-front information is generated and propagated. Finally, Section 6 gives a concluding discussion and an outlook.

2. Distribution of equipped vehicles and network topology

For a low market penetration, the positions of the IVC equipped cars can be assumed independent of each other. Even at high traffic densities, an equipped car will rarely encounter another equipped car. With the additional assumption of a constant overall traffic density ρ on all lanes of the analyzed driving direction, and for a given percentage χ of IVC vehicles, it follows that the number of IVC vehicles on a given road section is Poisson distributed. For convenience we define the density of equipped cars λ as \( λ = ρχ \). Assuming a maximum
broadcast range $r_{\text{max}}$ (which shall be the same for all equipped cars), the number $n$ of cars connected to a given equipped vehicle (the node degree) is distributed according to

$$f_{\text{Poisson}}(n) = \frac{\gamma^n}{n!} e^{-\gamma}, \quad n \in \mathbb{N}.$$  \hspace{1cm} (1)

The expected value $\gamma$ of $n$ is given by the length of the freeway stretch within broadcast range divided by the mean distance between equipped vehicles. For two driving directions with identical traffic densities, we have

$$\gamma = 4r_{\text{max}} \lambda.$$  \hspace{1cm} (2)

The average number and the variance of equipped cars in the broadcast range are both given by $\gamma$. For example, $\gamma = 1.5$ in case of an equipment level of $\alpha = 0.05$, a traffic density of 30 vehicles/km (in each driving direction) and a broadcast range of $r_{\text{max}} = 250$ m.

As a consequence of the Poisson distribution, the headways $\Delta$ between consecutive equipped vehicles are distributed exponentially:

$$f(\Delta) = \lambda e^{-\lambda \Delta} \text{ with } \lambda = \alpha \rho.$$  \hspace{1cm} (3)

This is very well supported by empirical data, cf. Fig. 1. Evaluating the data of single cars passing a freeway cross-section, it is possible to obtain the distribution of distances between IVC equipped vehicles for scenarios with different equipment levels. Even for a single lane, this distance is exponentially distributed for small equipment levels. However, for equipment levels above 20%, the form of the distribution becomes more and more similar to the Erlang/Pearson III distribution of vehicle headways [19].

![Fig. 1. Probability density of distances between IVC equipped vehicles based on single vehicle data for the freeway I-880. Each car entering the upstream boundary of the investigated freeway stretch has, with probability $\alpha$, been randomly and independently chosen to be an “equipped” car to reflect an IVC market penetration of $\alpha$. Based on the time headways $d_{\text{time}}$ between consecutive equipped vehicles, we have obtained the distance $\Delta$ for every equipped car $i$ via $d_i = d_{\text{time}}_{v_{i-1}}$, where the equipped car $i - 1$ is the predecessor of car $i$, and $v_{i-1}$ its velocity. The single vehicle data were recorded in 1993 at cross-section 6 (29 300 feet distance from Mariana) of freeway I-880, Hayward, California, in direction north [18]. Data of congested or light traffic (velocity $< 60$ km or flow $< 1000$ vehicles/h/lane) have been omitted. Only the right lane has been taken into account in (a) and (c). In (b) and (d), the three rightmost lanes from altogether five lanes have been considered.](image-url)
3. Message propagation

In order to be useful for receiver cars, traffic related messages normally have to travel upstream from the location, where they have been generated. The message can hop from one IVC car to subsequent IVC cars within the same driving direction—which will be called *longitudinal hopping*. Alternatively, the message hops to an IVC car of the other driving direction, which moves with the message upstream and delivers it back to cars of the original driving direction. The second mechanism, where vehicles of the opposite direction act as relay stations, will be referred to as *transversal hopping* (cf. Fig. 2). Although a mixture of these two mechanisms is possible, in the following we will restrict ourselves to the treatment of the “pure” mechanisms for simplicity.

3.1. Longitudinal message hopping

If there is an upstream receiver in the broadcast range of the sending car, a longitudinal hop is possible. However, for a message to be transported across a certain distance, a closed chain of IVC cars is necessary: every single distance between two subsequent IVC equipped cars must be smaller than the broadcast range, otherwise, the link is broken. Broken links are very likely for a low equipment level. The following example presents a more detailed analysis.

The probability of finding an upstream receiver for longitudinal hopping depends on the broadcast range \( r_{\text{max}} \). It is given by

\[
P(D < r_{\text{max}}) = \int_0^{r_{\text{max}}} f(D) \, dD = 1 - e^{-\lambda r_{\text{max}}}. \tag{4}
\]

Considering an overall density of \( \rho = 30 \) vehicles/km on two lanes, \( \alpha = 0.05 \), and \( r_{\text{max}} = 250 \) m, we obtain a probability of 31\% for a single message hop. If we require that the information should be available for a receiver who is \( r_u = 1000 \) m upstream of a detected traffic event, at least four message hops are necessary. The single hops are statistically independent from each other, thus the probability for four hops is given by \( [P(D < r_{\text{max}})]^4 \approx 1\% \). This serves as an upper bound for the connectivity over a distance of 1 km. The exact transmission probability is 10 times smaller, as it is likely that more hops are needed. It is given by the formula \([20]\):

\[
P_{\text{connect. } 1 \text{ km}} = 1 - \sum_{i=1}^{m} \frac{(-\lambda)^{i-1}}{(i-1)!} (r_u - i r_{\text{max}})^{i-1} \left[ 1 + \frac{\lambda}{i} (r_u - i r_{\text{max}}) \right] e^{-i \lambda r_{\text{max}}}, \tag{5}
\]

where \( m \) is the largest integer smaller than or equal to \( r_u / r_{\text{max}} \).

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**Fig. 2.** Generation and upstream propagation of traffic information on a freeway: when car “A” enters a traffic jam, it starts broadcasting a related message. This can be received by a subsequent car via longitudinal hopping (“LH”) or may be picked up by an equipped transmitter car “T” of the other driving direction via transversal hopping (“TH”). The latter may happen immediately or may take some time until a transmitter is encountered. In the latter case, the message travels with the transmitter “T” upstream, until it is delivered back to the original driving direction by back transversal hopping (“BTH”). In the main text, we compare the efficiency of the two message passing mechanisms of longitudinal and transversal hopping.
3.2. Transversal message hopping

With longitudinal hopping, a message either reaches its “destination” at once or never. In contrast, via transversal hopping, a message reaches always the destination point upstream of the position where it has been generated. But this is associated with a time delay. The message becomes available at this point as soon as the first encountered equipped car of the other direction, the transmitter, has moved a distance \( s^* = r_u - r_{max} \) upstream from the place of message generation. The remaining distance can be bridged via wireless communication (cf. Fig. 3). The time \( \tau \), after which this process is completed, depends on the initial position of the transmitter at the time the message is generated and on its velocity \( v_{tr} \). To make the message available, the transmitter has to cover a distance consisting of the two parts \( s_1 \) and \( s_2 \) (cf. Fig. 3). Thus, we obtain

\[
\tau = \frac{s_1 + s_2}{v_{tr}}.
\]

\( s_2 \) is given by

\[
s_2 = r_u - 2r_{max}
\]

(cf. Fig. 3), while the distribution \( f(s_1) \) of the stochastic quantity \( s_1 \), i.e., the first part of the distance, the transmitter has to cover, agrees with the gap distribution \( f(A) = \lambda e^{-\lambda A} \) between two IVC cars. This implies

\[
f(s_1) = \lambda e^{-\lambda s_1} \Theta(s_1),
\]

where the Theta-function \( \Theta(s_1) \) is 1 for positive arguments \( s_1 \), otherwise zero.

Let us now calculate the cumulative distribution \( P(\tau < t) \) of arrival times \( \tau \). According to Eq. (6), the message arrives at a time \( \tau < t \), if \( s_1 < tv_{tr} - s_2 \). Therefore, the probability that the information is successfully transmitted until time \( t \) can be calculated as

\[
P(\tau < t) = P(s_1 < tv_{tr} - s_2)
= \int_0^{tv_{tr}-s_2} f(s_1) ds_1
= \Theta(t - r_u - 2r_{max}/v_{tr}) (1 - e^{-\lambda(2r_{max} + v_{tr}t - r_u)}).
\]

Since \( f(s_1) = 0 \) for \( s_1 < 0 \) (see Eq. (8)), the cumulative distribution is zero if, in the case of a small value of \( t \), the upper bound of the integral in Eq. (10) becomes negative. This results in the Theta function \( \Theta(tv_{tr} - s_2) = \Theta(t - ((r_u - 2r_{max})/v_{tr})) \) in Eq. (11). Since the probability of a transmission before the time \( (r_u - 2r_{max})/v_{tr} = s_2/v_{tr} \) is zero, this is the minimal possible transmission time. This occurs, when the transmitter only needs to pass the distance \( s_2 \), i.e., if it is initially as far as possible upstream.

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**Fig. 3.** Initial spatial configuration and labeling of the distances: the sender has just detected a traffic-related event and broadcasts a corresponding message. The first encountered equipped car of the other direction, the transmitter, may be downstream (right) or upstream (left) of the sender, but in the latter case within the broadcast range \( r_{max} \) (left cutoff of the probability distribution). If the transmitter is out of the broadcast range (for large \( s_1 \), the message will not be received immediately. The time, when the message is picked up by the transmitter does not directly affect the time \( \tau \) which is needed to deliver the message a distance \( r_u \) upstream of the initial sender position. It depends on \( s_1 \); in order to make the message available a distance \( r_u \) upstream of the initial sender position, the transmitter has to cover a total distance of \( s_1 + s_2 \), where \( s_1 \) is a stochastic part reflecting the stochastic initial position of the transmitter, and \( s_2 = r_u - 2r_{max} \) is mainly determined by the claimed minimal delivery range \( r_u \).
In Fig. 4, the information transport within the same driving direction ("longitudinal hopping") is compared to the information transport via a transmitter in the opposite driving direction ("transversal hopping"). In the first case, the message can be more or less instantaneously available a certain distance ru upstream of a recognized traffic event (if we neglect the broadcasting time). But the probability for the successful establishment of a complete information chain (i.e., for connectivity) is small, if the equipment rate is low. In the case of transversal hopping, the message needs at least 18 s, but after 36 s, the message is available with a probability of about 50%, when the velocity of the transmitters is assumed to be vtr = 90 km/h. The minimal time for the message transfer is \( (r_u - 2r_{\text{max}})/v_{\text{tr}} = 18 \) s.

In Fig. 4, the information transport within the same driving direction ("longitudinal hopping") is compared to the information transport via a transmitter in the opposite driving direction ("transversal hopping"). In the first case, the message can be more or less instantaneously available a certain distance ru upstream of a recognized traffic event (if we neglect the broadcasting time). But the probability for the successful establishment of a complete information chain (i.e., for connectivity) is small, if the equipment rate is low. In the case of transversal hopping, the message needs at least 18 s, but after 36 s, the message is available with a probability of about 50%. A 36 s old information 1000 m ahead of the event is still very valuable: for example, in 36 s a possible disturbance of the traffic flow may travel (with a characteristic speed of approximately 15 km/h) 150 m upstream. Hence, for the receiver of this information, there are 850 m left to react to the traffic event (e.g., a stop-and-go wave).

4. Microscopic simulation of inter-vehicle communication

The analytical result (11) for the distribution of message arrival times further upstream can be tested directly by implementing the mechanism of message generation (i.e., of sending and receiving) in a simulation. To this end, we have carried out a multi-lane traffic simulation of a 10 km freeway stretch with two independent driving directions and altogether four lanes. We have used the intelligent driver model (IDM) [21] as a simple car-following model complemented by a lane changing algorithm [22]. In order to introduce heterogeneity to the driver–vehicle units, the desired velocities have been chosen Gaussian distributed with a standard deviation of 18 km/h around a mean speed of \( \nu_0 = 120 \) km/h. The other parameters have turned out not to be relevant for the resulting statistics. Furthermore, we have used open boundary conditions with a constant inflow at the upstream boundary of \( Q = 1240 \) /h/lane.

The microscopic simulation approach allows for a detailed modeling of the message broadcast and receipt mechanisms of IVC equipped vehicles. To obtain the statistics of message propagation, the equipped vehicles generate a test message while crossing the position \( x = 5 \) km. The equipped vehicles in the opposite driving direction are used as transmitter cars enabling a "transversal" message hopping for a fast information propagation in upstream direction. The percentage of vehicles equipped with the IVC device is varied and the traffic density measured by "virtual" detectors at specific freeway cross-sections. In Fig. 5, the results of the
5. Upstream transport of traffic-related information via transversal hopping

Let us now apply the message generation and propagation mechanism to a specific traffic scenario. Again, we have simulated the two driving directions of an altogether four-lane freeway. In one driving direction, we have triggered a wide moving cluster (also called a “Moving Localized Cluster” [23,24]), while traffic was freely flowing in the other driving direction. Two types of messages have been generated: (i) if the velocity of a vehicle equipped with an IVC device dropped below 30 km/h, the car started to broadcast the message “start of traffic jam” with the time and position of its detection. (ii) If the velocity exceeded the velocity 30 km/h, the message “end of traffic jam” was started to be broadcasted.

The spatiotemporal traffic dynamics and the processes of sending and receiving messages are illustrated in Fig. 6. Due to the low equipment rate of $\alpha = 3\%$, the equipped vehicles have an average distance to each other that exceeds the broadcast range $r_{\text{max}}$ of the IVC device. An upstream message propagation only within one driving direction would, therefore, lead to a fast breakdown of the information chain (see Fig. 6), as stated in Section 3.1. Thus, we have used IVC-equipped vehicles as transmitters in the other driving direction. Fig. 6 enumerates the generated messages and shows their delivery to a specific vehicle. Remarkably, the considered vehicle receives the first message about the traffic congestion already 2 km before encountering the traffic jam. The information is confirmed and updated by subsequent messages provided by other vehicles. The up-to-date information about the expected traffic situation allows for a very accurate individual information about the approaching traffic jam as well as the expected travel time through the congested area. This could be used to inform drivers or to operate a strategic ACC system [15].

6. Summary and outlook

Vehicles exchanging (traffic) data via wireless communication can be regarded as coupled material and information flows in complex networks. The changing topology of ad hoc networks for decentralized information exchange affects strongly the dynamic process running on the network, i.e., the data flow. We simulation are compared to the analytical results (11) based on the Poisson approximation. The simulation results show an excellent agreement with our analytical calculations.
have investigated the generic scenario of upstream message propagation where a low percentage of cars is equipped with IVC. The weak connectivity within one driving direction can be overcome by using cars of the other driving direction as relay nodes which, however, involves a small time delay. For example, for an equipment rate of 5%, a traffic-information message will be passed 1 km upstream within 36 s with a probability of 50%. For comparison, a complete information chain (connectivity) exists within one driving direction only with a probability of 0.1%. Our analytical estimations have been strongly supported by results of microscopic traffic simulations.

The purpose of inter-vehicle communication is an adaptive behavior to the expected traffic situation. This means to approach traffic jams with decreased speeds, to accelerate faster out of traffic jams and to dampen stop-and-go waves. Future ACC systems may support these features and thereby reach a higher safety, stability and capacity of traffic flows. In this way, information flows in ad hoc traffic information networks may change the traffic dynamics. The modified motion of cars (network nodes) may also change the network topology and, therefore, influence message propagation. Consequently, inter-vehicle communication is characterized both by a dynamic information flow on a network and by a changing network topology, with non-linear feedbacks among the two. Due to their complexity, interacting information and material flows in networks will certainly stay an interesting research subject in the future.
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