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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.

Keywords: Inter-vehicle communication; Ad hoc networks; Traffic flow; Traffic information; Jam detection

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 α 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 $\lambda = \rho\alpha$. Assuming a maximum