Information in motion: road vehicles as wireless relay stations for an ad hoc communications network

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Abstract: There is growing interest among automobile engineers and wireless communications researchers in the concept of a Vehicular Ad-hoc NETwork (VANET). Each motor vehicle on the road today provides a natural platform for mobile communications. When equipped with suitable on-board device, the population of vehicles in a busy area becomes a wireless network capable of relaying signals across considerable distances, without the need for a central transmitter.

Among the applications so far suggested are the propagation of safety warnings such as icy road conditions, crime prevention, surveillance aimed at public security, together with less urgent passenger services, and even congestion management. To determine whether and how such a system would function, it is necessary to model two distinct kinds of network simultaneously - the road system and the wireless network. The challenge is significant, not least because of the many factors involved. The authors have adapted a cellular automaton (CA) approach, which is used to investigate the relationship between communication, contention/interference and mobility. The results show how mobility affects network performance and how the processing gain G can be used to design effective coverage areas which maximize the total network throughput. Most important for safety-critical applications, a VANET can break down under congested road traffic conditions because of radio interference among the vehicles.

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1. Introduction

People are accustomed to think of a wireless network as a system in which all communication is channelled through a central facility, so that users must be within range of a central transmitter to send and receive messages. Recently, however, communications specialists have found ways of propagating information directly among the users themselves. Mobile-Ad-hoc NETworking technology (MANET) allows a digital signal to be relayed via a chain of nodes to its destination even though the source node and destination node are not directly in radio contact. In fact, the nodes can be moving about, but since each node is required to relay information only to its neighbour, the power requirements are relatively small. Moreover, alternative pathways among the nodes provide a high degree of redundancy in the event of a local breakdown. A proprietary system MESH has recently been installed in Glasgow in the UK for co-ordinating the operation of traffic lights at junctions in this way (Anon, 2006).

Vehicular Ad-Hoc Networks

Automobile engineers have now joined communications specialists in developing a related concept: the Vehicular Ad-Hoc Network or VANET (Marfia et al., 2007a;b; Nandan et al., 2005; Karnadi et al., 2007). Almost every motor vehicle on the road today carries an electrical power source together with an assortment of microprocessors that are needed to carry out sophisticated functions such as engine management. It therefore provides a natural platform for digital communication. Suitably equipped, the vehicle becomes a wireless node, allowing connection to any other vehicle within range, which varies from 100 m to 300 m depending on whether there is a direct line of sight between them. As cars fall out of the signal range or drop out of the network, other cars will replace them, effectively creating a mobile internet that can operate without any supervisory infrastructure - a ‘bush telegraph’ for road users.

VANET technology is not in itself a solution, but rather a tool that can be exploited to make possible a range of traffic control systems and travel services, all of which have in common the need for individual vehicles to communicate either with one another, or with a central facility. However, ad hoc networks suffer from a potential drawback: all the nodes must transmit and receive within the same frequency band. Consequently, if cars get too close together, the signals will interfere with one another and the transmission will be lost.

Aims and objectives

In comparison with other types of ad-hoc network, the development of an effective VANET system presents unique challenges, a discussion of which can be found in Nekovee (2005). These include

(a) end-to-end network connectivity

(b) routing and information dissemination protocols

(c) the wireless communication technology

(d) the vehicular traffic model

The aim of this paper is to model key features of such a network in order to understand the way in which vehicular traffic conditions influence the efficiency of communication, and in particular, the conditions under which breakdown is likely to occur. But a VANET system can be used for many different applications, and the optimum set-up varies accordingly. For example, some applications can sustain gaps in communication, while others cannot. A system for broadcasting congestion warnings can deliver benefits even if messages do not reach every vehicle on the network, whereas in a system for managing emergency services, the consequences of a communications failure could be disastrous. Likewise, the choice of routing protocol (the way in which messages are routed from source to destination) depends on the application. Hence the choice both of (a) performance criteria for connectivity and (b) the routing protocol will vary according to the use to which the system is being put. Here, we shall be primarily concerned with those aspects of operation - (c) and (d) - that are common to all applications, leaving items (a) and (b) to be dealt with in a separate paper.

The rest of this paper is organized as follows. Section 2 gives a brief introduction to cellular automata. In Section 3, we describe how a cellular automaton is used as the basis of our integrated simulation model, focusing initially on the behaviour of traffic in an urban grid network. We then introduce the wireless functions and compare our approach with several earlier ad-hoc network models. Section 4 discusses the results. In section 5 we discuss potential VANET applications and in Section 6 we summarise our conclusions and suggest directions for future research.

2. Previous work

Cellular automata and road traffic

A cellular automaton (CA) is a mathematical model of the interactions among a group of objects, usually in two- or three-dimensional space. Individually, the interactions may be represented in a simplistic way, so that the evolution of the system can be simulated on a computer to throw light on collective behaviour.

Cellular automata have been used to model complex phenomena in many scientific fields including biology, chemistry, astronomy and computer science (Ganguly et al., 2003). Cellular automata have also been used to study road traffic. The most common approach has been to represent a road as a series of discrete cells, each of which can hold only one vehicle at a time. Time is divided into equal slices. During any given time slice, a vehicle can move to the next cell or remain where it is. Gordon and Newell (1967) and Wright (1975) investigated flow characteristics by assigning to each vehicle a fixed probability of advancing from one cell to the next given that the cell ahead was free. More recently, the work by Nagel and Schreckenberg (1992) and Santen et al. (1998) has introduced more elaborate rules that simulate real vehicular movement more closely, stimulating further work by, for example, Chopard et al. (2003). In all these studies, the road network is linear or one-dimensional (in Wright's case, it was a closed circuit).

By comparison, the simulation of a two-dimensional network requires powerful computing facilities. Usually, the city is represented as a rectangular grid of cells arranged like a chessboard whose axes are aligned east-west and north-south. In the study by Biham and Middleton (1992), arrivals are deterministic: during each time slice, a fixed number of vehicles is injected into the grid and the vehicles progress according to simple rules which mimic traffic behaviour. Each vehicle is assigned a specific direction of motion, and carries on moving in that direction whenever it is possible to do so. The stochastic version by Molera et al. (1993) differs only in that vehicles can change direction at any junction. The direction of movement is controlled by a random variable. Both these models reveal a transition point that separates a low density phase where vehicles move freely, and a high-density phase where the vehicles form an area-wide traffic jam. This phase change has implications for communication as outlined later.

Wireless networks

A great deal of research has been carried out on the capacity of ad hoc wireless networks, that is to say, networks where messages are relayed between nodes rather than through a central facility: see, for example, Camp et al. (2002), Zander and Kim (2001), and Lea and Zhang (2004). In a system of this kind, at any particular time a node may perform any one of three distinct roles: as the originator or source of a message, as the recipient or destination of a message, or as a passive relay station. For brevity, we shall refer to a source node as S and a destination node as D.

Gupta and Kumar (2002) study the capacity of fixed ad-hoc networks, where nodes are randomly located but do not move. They show how throughput per S-D pair decreases as the density of nodes per unit area increases. In contrast, Grossglauer and Tse (2001) explore the effects of motion in a system in which nodes move about at random and the communication system is narrowband (i.e., it has a low frequency bandwidth that limits throughput). For nodes that are widely separated, direct communication is often impeded owing to radio interference - other vehicles are trying to send messages using the same frequency band at the same time. Moreover, for any given density of vehicles on the road network, the impact of interference is heightened if the traffic slows down. To put it the other way round, mobility improves communication, which is one of the distinguishing features of a VANET. The issue of 'blocking', where a vehicle cannot move because its target cell is already occupied, is not dealt with explicitly. Additionally, the authors show that the tendency for throughput to decrease with increasing node density can be offset by splitting the packet stream among different relay nodes.

None of these studies use cellular automata, which have been applied only recently in the wireless field. Cunha et al. (2005) and Yuan et al. (2003) investigate topology issues in a wireless sensor network. Orenstein and Marantz (2007) apply a CA model to radio propagation in an ad-hoc environment, confirming that mobility encourages communication, and that nearest-neighbour communication is more effective than direct communication with non-neighbouring nodes.

Here, we shall confirm the key findings of Grossglauer and Tse (2001) and then extend the analysis to the spread-spectrum case. 'Spread spectrum' refers to the practice of allowing several communication channels, all at slightly different frequencies within the overall bandwidth of the system, to be used at the same time, thereby increasing the capacity of the system. In such a case, the processing gain, defined as the ratio of system bandwidth to channel bandwidth, is greater than one. We explain how mobility affects network performance and show how the processing gain can be used to design elastic coverage areas which maximize the total network throughput for a range of network densities.

3. The integrated model

As with the area-wide models just mentioned, the road network in this paper is a square lattice as shown in Figure 1. Under these circumstances, there is no topographical variation and therefore no 'map' of the sort that readers of this journal have come to expect, although we hope to extend our approach to more realistic road network configurations in due course.

One reason for this simplistic approach is that we are dealing with two networks simultaneously. First, the vehicles are moving around a fixed road network according to prescribed rules. Second, the messages are moving around a communications network whose nodes are the vehicles themselves, and whose shape is therefore changing continually (see Figure 1). Note that for practical purposes, there is no delay in the propagation of a signal between any two points of the wireless network. During any given time slice, as long as there exists between the source and destination nodes a chain of relay nodes that are in radio contact with one another, each digital character of the message is transferred almost instantaneously.

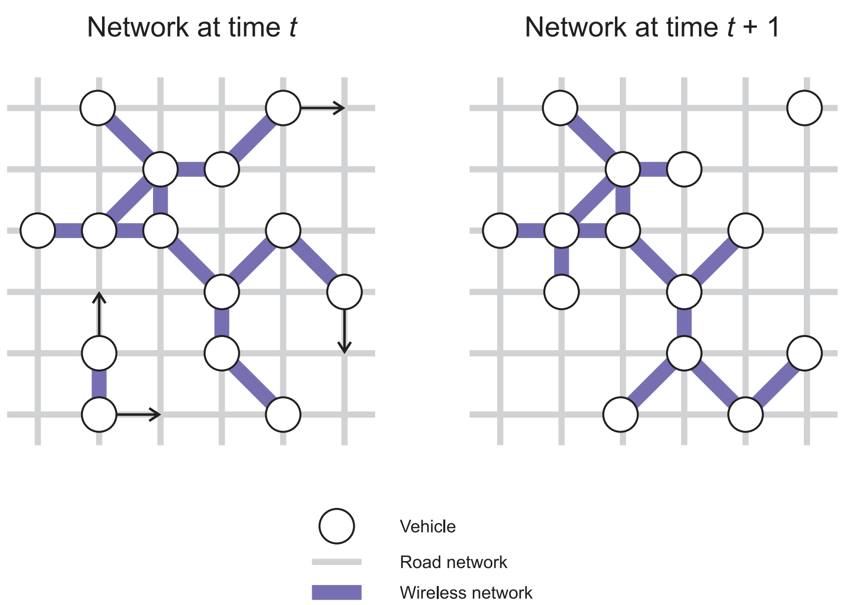

Figure 1. The relationship between the road traffic network and the wireless network.

Road traffic

We have extended the basic model of Molera et al. (1993) to describe an urban grid network with four possible directions of travel: north, south, east and west. The movements of each vehicle are governed by a random number generator. During any given time slice, a vehicle may stay in place (with probability p_{stay}), or it may move to a neighbouring 'target' cell in any of the four possible directions DN with probability given by

$$p_{DN,move} = (1 - p_{stay})/4 \tag{1}$$

If, however, the target cell is occupied by another vehicle, it must remain where it is. This model simulates a random walk through the network and it encapsulates two features of urban traffic: (a) blocking between vehicles, and (b) delays arising from sources external to the traffic stream, such as the traffic signals at junctions. Figure 2 shows examples of different events occurring to different vehicles during a typical time slice, including vehicles arriving and departing at the grid boundary. Traffic is injected onto the grid at a constant rate via a single Poisson process with mean μ, the arrivals of individual vehicles being distributed around the entry points on the perimeter in a random fashion.

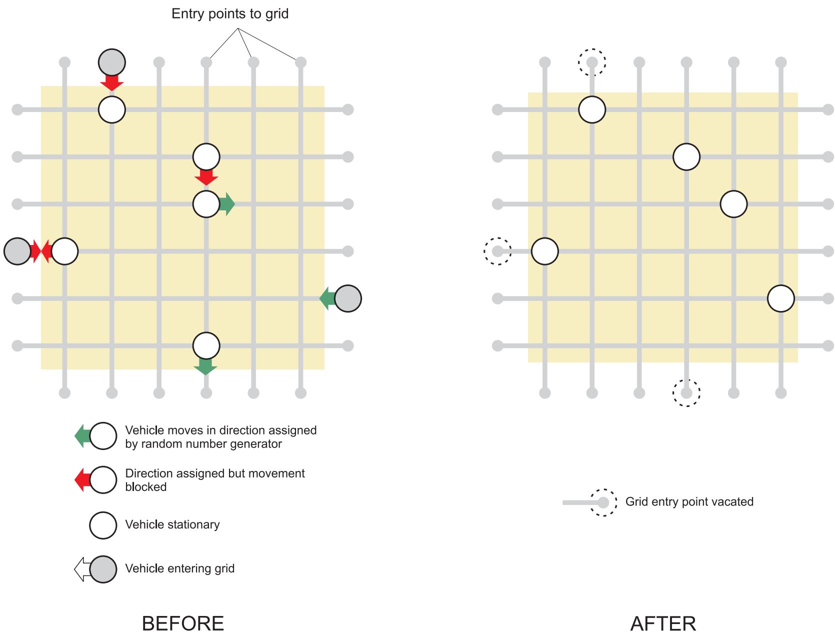

Figure 2. Arrivals, departures and movement on the road traffic network.

Wireless propagation

A central theme in our model is the concept of a neighbourhood. For any given vehicle S at a given moment, there are three distinct types of neighbourhood:

a) The *mobility neighbourhood*: the set of possible locations that the vehicle can move to during any one time slice (N, S,E, W).

b) The *communication neighbourhood*: the set of nodes that are within its wireless range, and

c) The *interference neighbourhood*: the set of nodes that contribute towards interference with radio reception for that vehicle.

As one might expect, in our model, the communication neighbourhood is larger than the mobility neighbourhood: the latter includes only the four cells immediately bordering the cell occupied by vehicle S, whereas the communication neighbourhood additionally includes the four diagonally neighbouring cells NW, NE, SW, SE. We shall refer to this as *single-hop* communication. In principle, with a more powerful transmitter, vehicle S could transmit directly to vehicles further away, in non-neighbouring cells, a point that will be explored later. We shall refer to this as *extended-hop* communication. Note that in this paper, the number of 'hops' refers to spatial separation; other authors use it in a different sense, to mean the number of stages in relaying a message between vehicle S and vehicle D.

In a study of wireless transmission in an ad hoc network, it is necessary to make some assumptions about the information 'load': the number of messages to be transmitted or relayed by each vehicle per unit time. Here, we assume that the rate is fixed independently of other factors such as the density of nodes on the network. Each message is broken down into packets, and then each packet is routed independently via the route with the strongest signal strength. The total throughput achieved within the VANET as a whole is defined as the number of packets successfully transferred per second, and this is one of the two parameters that we use as overall measures of performance.

Model Parameters

The operation of the simulation model is controlled by two sets of parameters, one relating to vehicle flow on the road network, and the other to wireless communications. Both are listed for reference in Table 1, together with two output parameters that we use as measures of the overall performance of the wireless system. A more detailed description of these parameters can be found in Orenstein and Marantz (2007), which also gives derivations for the formulae used to derive some of the results described in this paper.

Like that of Grossglauer and Tse (2001), our model only considers large-scale path-loss characteristics, i.e., the power of the signal declines with distance between emitter and receiver according to a specified functional relationship independently of local topography. The model does not take into account more subtle effects such as reflection and refraction leading to multiple signals (multipath fading), or shadowing effects caused by obstructions such as hills or buildings.

	Symbol	*Definition*
Road Traffic Network Parameters	p_{stay}	Probability that a vehicle remains in its current location during any time slice
	μ	Mean total demand in vehicles per time slice (Poisson arrivals, distributed around the grid perimeter)
	n	Size of grid (in this study, fixed at 20, leading to a grid of 20 x 20 = 400 cells)
	M	Mobility neighbourhood (since vehicles can only move between neighbouring cells, M is set to 1 in this study)
Wireless Network Parameters	$N_T = 1, 2...$	Transmission neighbourhood (includes diagonally neighbouring positions). The value is larger than 1 for extended-hop communication.
	$N_R = 1, 2...$	Interference neighbourhood (includes diagonally neighbouring positions). The value is larger than 1 for extended-hop communication.
	$Pi(t)$	Power of node i at time t, initially set to $Pmax = 1$ (watts). This corresponds to the worst case for interfering communications.
	a	Path loss exponent
	D	Geographical distance between nodes (units of the grid)
	G	Processing gain ($G > 1$) See definition below
	$\sigma^2 = 5 \times 10^{-15}$	Additive White Gaussian Noise (AWGN) in watts
	R	Normalized data rate equal to 1 packets/sec
Simulation Performance Parameters	ϕ	Wireless node density = no of occupied cells/n^2 (this is numerically equivalent to the road traffic density expressed in vehicles per cell)
	TN	Total network throughput = $R\times$ (total number of allowable connections)

Table 1. Key parameters in the integrated model.

Referring to Figure 3, we assume that node S can transmit data to node D if the strength of the signal received by D is greater than a randomly generated threshold, β, $(0 \leq \beta \leq 1)$. A connection is then established, and information is transferred between them at a fixed rate (R packets/s). If there is more than one possible candidate connection, then the stronger one is used. The probability that a node's data packet is received successfully, without errors at the decoder, is represented by a mathematical function whose form depends on the characteristics of the transmission system (Rodriguez, 2003). Further details are given in Orenstein and Marantz (2007).

At the end of each simulation cycle, the model records (a) the total number

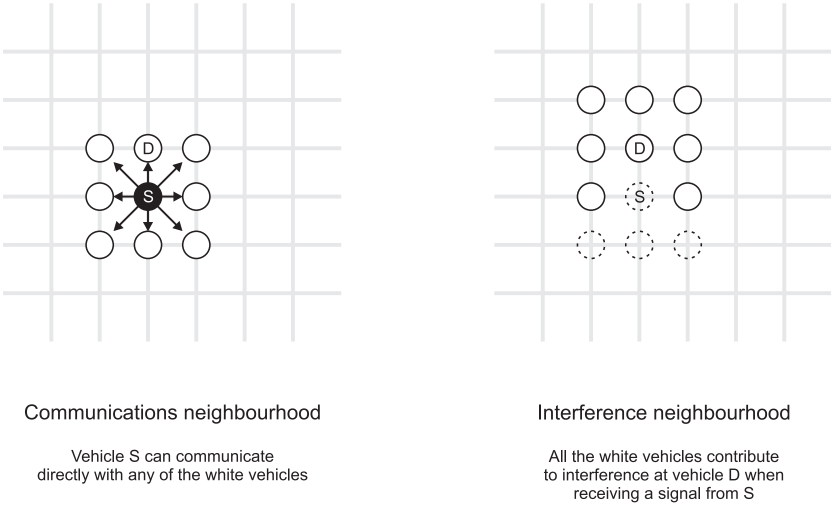

Figure 3. Communications and Interference neighbourhoods.

of established connections, (b) the total normalized network throughput TN, which is the total number of connections multiplied by the data rate of R packets/s, and (c) the wireless node density. The latter, denoted by ϕ, is equal to the number of occupied sites divided by the maximum number of possible sites in the grid. Since we are assuming here that each vehicle is equipped as a wireless node, provided they are measured in the same units, the wireless node density and the vehicular traffic density measured in vehicles per cell are equal.

4. Results

Effect of wireless node density

The results in Figure 4a show that as the wireless node density increases, so does the normalized network throughput, but only up to a point. The maximum throughput, which we denote by $TN*$, occurs at a particular value of the node density, which is denoted by ϕ_{opt}. In the case of single-hop communications, where each device may communicate with one of eight vehicles in its immediate neighbourhood, this maximal throughput occurs when $\phi_{opt} \approx 0.30$. Increasing the number of vehicles has the effect - at first - of promoting communication, but in congested traffic the wireless network effectively shuts down because of increased overcrowding (and therefore interference) among the nodes.

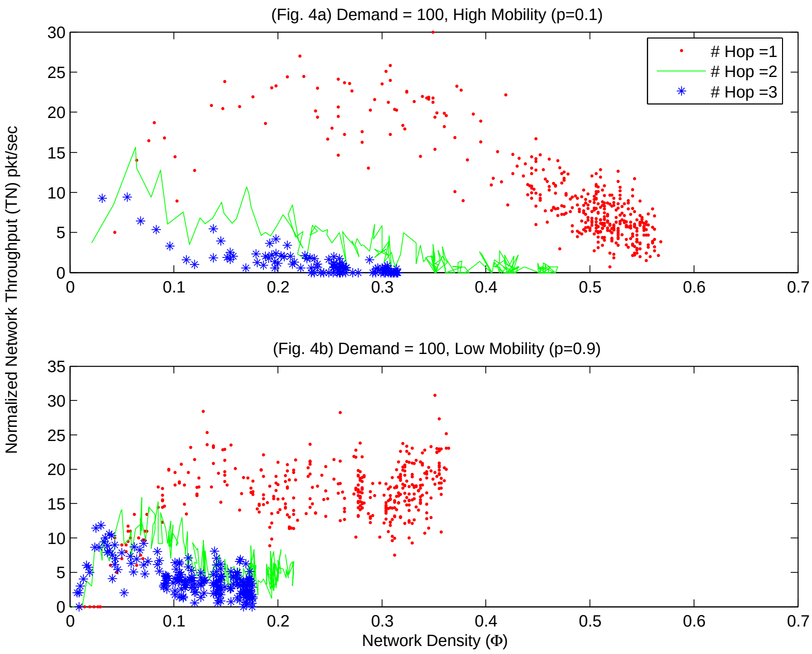

Figure 4. Effect of mobility on communication with fixed processing gain G=10.

Extended-hop communication only makes matters worse. If, for example, a device can 'talk' to vehicles located two hops away, the scope for interference increases and the total network throughput is significantly reduced. The optimum node density ϕ_{opt} is also reduced, in this case to a value of roughly 0.13. The optimum node density is even less for three-hop communication.

Impact of Mobility

Communication is also affected by mobility. Again referring to Figure 4b, with low mobility, no communication is possible once the network reaches a density of $\phi \approx 0.35$. By contrast, with high mobility (Figure 4a), some throughput (albeit suboptimal) is possible up to network densities of $\phi \approx 0.55$. This result confirms the theoretical analyses in Grossglauer and Tse (2001). Table 2 summarizes the values of ϕ_{opt} and $TN*$ for selected mobility scenarios. Even with quite high node densities, communication can still take place provided the vehicles are moving freely.

Mobility Level	N° of hops	ϕ_{opt}	$TN*$ (packets/s)	Density ϕ for which network fails irretrievably
High	1	0.30	250	0.55
Low		0.13	200	0.35
High	2	0.10	150	0.48
Low		0.08	150	0.22
High	3	0.07	100	0.31
Low		0.07	100	0.18

Table 2. Impact of communication/interference range on critical network density ϕ_{opt} and corresponding maximal throughput $TN*$.

At first sight this may seem surprising. The explanation lies in the fact that traffic congestion implies wireless interference. In our treatment, low mobility is equated specifically with a high value of p_{stay}, in other words, a high probability of a vehicle being forced to remain in position by external factors (such as traffic signals) rather than moving to an adjacent site, during any given time slice. If vehicles are frequently delayed by obstructions of this kind, they in turn will obstruct other vehicles and generate local queues. This in turn implies a high proportion of vehicles whose messages are subject to interference through local overcrowding, and hence a reduced wireless throughput.

Effects of processing gain (spread spectrum case)

In general, increasing the processing gain (a scarce resource) improves the total network throughput which is maximized at a particular network density. Figures 5a-c show that when the processing gain is increased, (a) the total network throughput increases proportionately, and (b) the feasible communication range is extended. We summarize the critical values of ϕ_{opt} and $TN*$ for each processing gain level and communication range in Table 3. The data suggests that for single-hop communication the optimal network throughput increases proportionately with higher processing gains and that communication is possible as long as occupation density is less than 70%. The effects can be seen graphically in Figure 5a. Figures 5b-5c indicate similar trends but they highlight the point that with extended-hop communication, both the maximal throughput and network sustainability levels are considerably reduced.

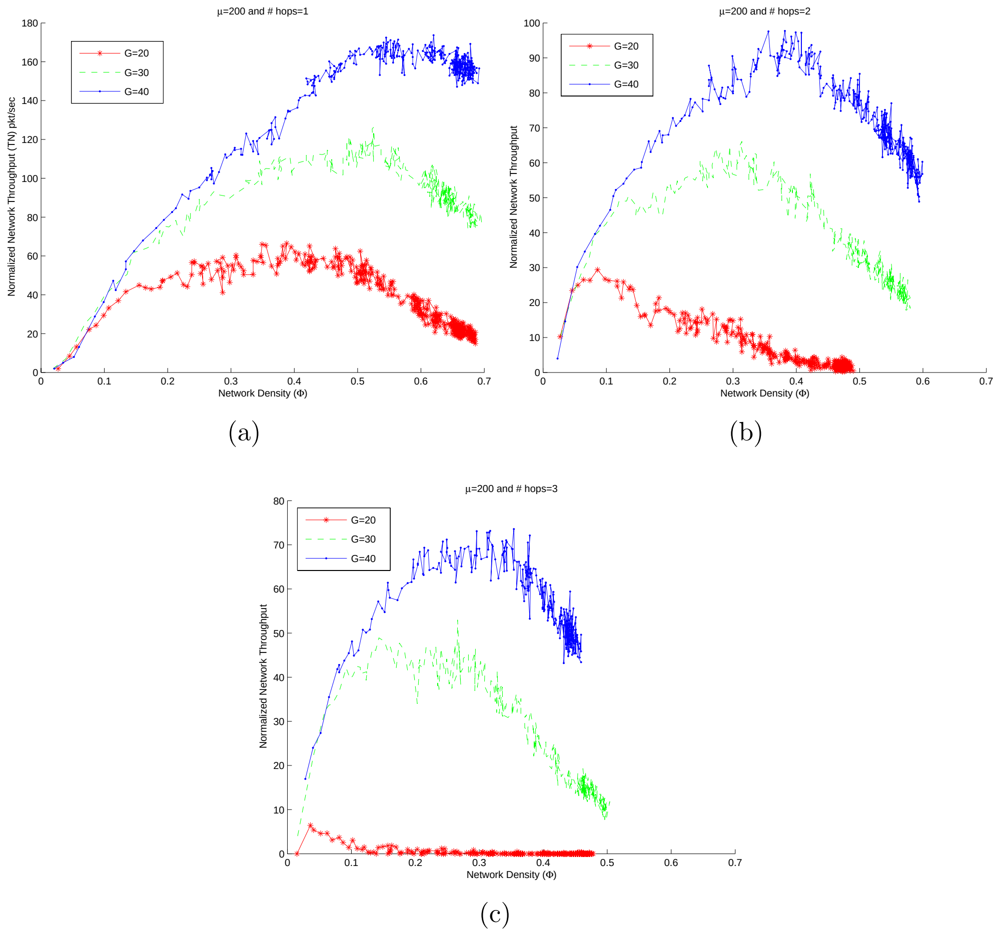

Figure 5. Relationship between the processing gain and the communication range operating points depending on network conditions.

These results suggest that it may be possible to use the processing gain adaptively depending on a wireless network administrator's performance goals. For example, for a minimum quality of service guarantee of $TN* = 3000$ packets/s, one can allow for communication across two-hops providing $G = 40$ or, one can restrict communication to single-hop mode by using $G = 30$. The preferred mode will depend on network performance goals and traffic conditions.

	G	ϕ_{opt}	$TN*$ (packets/s)	Density ϕ for which network fails
Single-hop	20	0.35	1000	0.70
	30	0.48	3100	0.70
	40	0.60	6500	0.70
Two-hop	20	0.10	500	0.48
	30	0.30	1750	0.58
	40	0.40	3900	0.60
Three-hop	20	0.05	100	0.47
	30	0.25	1250	0.50
	40	0.35	2800	0.47

Table 3. Effect of increasing processing gains on communication range and total network throughput level.

5. Potential Applications

Most of the applications for VANET considered so far have to do with safety: for example, the propagation of warnings about hazardous road conditions such as ice, floods, and accidents. Other applications include the pre-payment of parking charges and road tolls, internet access, and congestion warnings. There appears, however, to have been little consideration of how services of this kind would actually operate. The communications requirements vary widely depending on the application.

We have found it helpful to divide applications into two distinct categories, the first covering 'top-down' applications such as road hazard warnings, and the second, non- safety critical services that passengers want and might be prepared to pay for. Applications within either category can also be sub-classified according whether (A) they take place autonomously without help from any external agency, or whether (B) they need to be routed through and processed by a central bureau.

Highway management services

All of these are top-down category B services. In all likelihood, the first systems to go into operation will be installed in police cars, fire engines and ambulances to provide life-saving communications between emergency personnel in situations where co-ordination is required. Less widely discussed but possibly just as important are applications to do with security and protection from crime and terrorism.

One of the most ambitious but potentially beneficial applications concerns congestion detection and management. Vehicle speeds are already being monitored using Automatic Licence Plate Reading cameras at fixed points along major roads in the UK and other countries. However, VANET offers a richer source of data, from which one can gauge journey times on alternative routes around a traffic jam by piecing together information received from different vehicles around the network.

Passenger-driven services

In principle, a VANET could also be used to make travel more convenient or more pleasant, providing access to multimedia and internet facilities so that passengers can use email and surf the Internet. Internet access would enable many other applications including automatic pre-payment for parking charges and road tolls. Exactly how the passenger interface might work, and how the costs of the system might be allocated, remains a topic for future research. What seems clear, however, is that passenger-driven services will be crucial in establishing a platform for all the other services presently under consideration, most of which require a minimum percentage of vehicles to be equipped with on-board wireless units in order for effective communication to take place. Decisions made now about the specification and performance standards for these wireless units could have long-lasting effects.

6. Conclusions and Further Work

In this paper, we have proposed an integrated model to study some of the emergent properties of a Vehicular Ad-hoc NETwork, based on a cellular automaton approach. The main results can be summarized as follows:

- Mobility improves communication and postpones communications breakdown. Removing external obstructions to vehicle movement helps to maintain information transfer at higher densities than would otherwise be possible.

- At a particular density of vehicles, the total network throughput is optimal but falls beyond this critical density.

- The processing gain parameter can be used to control the communication range as well as to increase the level of throughput. With limited processing gain, single-hop communication achieves highest throughput levels and our results suggest that the processing gain should be elevated in order to extend the coverage region across wider areas of the network or to boost the total throughput.

These conclusions are subject to caveats arising from the simplistic nature of our model, both in terms of the way vehicles move and in terms of the likely pattern of demand for communication in real systems. On urban road networks, vehicles tend to move around in 'platoons', that continually expand and contract as they move through obstructions such as traffic signals. For some of the time, vehicles are close together, but there are frequently long gaps that signals cannot bridge. Moreover the demand for signal processing is likely to vary with the number of vehicles on the network, in ways that depend on the application envisaged. Nevertheless, the qualitative features we have observed point towards aspects of VANET behaviour that merit investigation with more realistic models.

In addition, our model does not capture delays that occur as signals are relayed from one vehicle to the next, which can be important under certain circumstances. Nor have we explored the potential benefits of 'broadcasting', whereby each node in the network communicates with *all* devices in its neighbourhood as opposed to selecting the best connection. Finally, our model does not take into account signal losses arising from the terrestrial environment such as multi-path fading or shadowing. All these are topics for future research.

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