Sensor networks on the road: the promises and challenges of vehicular ad hoc networks and grids

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One of the most exciting application areas of wireless ad hoc networks is the automobile sector. Ad hoc network technology will be used in the near future in the car's onboard communication unit in order to collect real-time data on traffic and road conditions from a variety of onboard sensors. Areas of application include services like safety warning systems, traffic control, and real-time traffic re-routing by intelligent traffic management systems. In this paper unique features and challenges that distinguish these systems from other types of ad hoc sensor networks will be discussed. We will also consider possible applications of wireless Grids in addressing the data aggregation and processing challenges that ubiquitous traffic monitoring and management systems will face. Some of the discussion will be based on our own experience with an ongoing collaborative project at BT Research in the area of Ubiquitous Traffic Telematics (Traffimatics).

PACS numbers:

I. INTRODUCTION

Vehicular ad hoc networks (VANET) are created by vehicles equipped with short and medium range wireless communication technology [1]. Communication is possible between vehicles within each other's radio range, and with fixed gateways along the road. These type of networks will be used in the future to collect real-time data on road conditions and traffic from a variety of onboard sensors. Some of the important applications of the resulting sensor networks are safety applications including collision and other safety warning systems [3, 4, 18], driver assistant and information systems and, further down the road, intelligent traffic management systems. Such systems will feed sensor data collected from vehicles and roadside sensors into traffic analysis and simulation software and use the result for control and management of traffic on the fly.

The opportunities for VANET are growing rapidly with many vehicle manufacturers and their suppliers actively supporting research and development in this area. In the US, the FCC approved 75 MHz of spectrum for inter-vehicle communications (IVC) and vehicle-to-roadside communication (VRC), known as Dedicated Short Range Communication (DSRC). The resulting DSRC system is expected to be the first wide scale VANET in North America. In Europe several national and European projects have been conducted, including the Fleetnet project in Germany [5]. In Japan two DSRC standards have been adopted and the Japanese car manufacturers are working with governments on an ambitious Advanced Safety Vehicle Project [7]. Here at BT Research in UK we are involved in a collaborative project with industrial and academic partners on ubiquitous traffic telematic system, or traffimatics [20, 21].

Creating high-speed, highly scalable and secure vehicular sensor networks presents an extraordinary challenge due to a combination of highly dynamic mobility patterns, which result in highly dynamic network topologies, combined with the high velocities that can be involved [2]. On the other hand, certain limitations commonly assumed in other ad hoc sensor networks are not present in these systems. For example, vehicular sensor networks have access to ample computational and power resources within the network itself, and can utilize high-performance wireless communication and advanced antenna technology. Finally, it can be expected that a significant fraction of vehicles will have an accurate knowledge of their own geographical position, by means of GPS.

The aim of this paper is to provide a short overview of the main networking challenges that vehicular sensor systems are facing to date, and to describe some of the exciting promises they hold in application such as traffic and driver safety mechanisms and ubiqitious traffic monitoring and management systems. We will also briefly discuss the promises of (wireless) Grids in addressing the data aggregation and processing challenges that such ubiquitous traffic monitoring and management systems will face.

The rest of this paper is organized as follows. In section II safety and traffic management applications of vehicular sensor networks will be discussed along with some examples. Section III is devoted to networking and wireless communication challenges of vehicular sensor systems. In section IV we discuss possible applications and integration of Grids with vehicular sensor networks. We close this paper in section V with conclusions.

II. APPLICATIONS

Sensors in cars can provide information on both instantaneous and time-averaged speed of the car as well as its position. The position information can be obtained either directly using onboard GPS capability, if this is available, or based on information received from neighbouring vehicles which have GPS. The sensors can also provide information on local traffic density and instantaneous front and back headways. These sensors can form a network on top of the VANET communication structure. Broadly speaking proposed applications that are designed to benefit from such vehicular sensor networks can be classified into safety applications and traffic monitoring and management systems.

Safety applications

These applications exploit the exchange of sensor data between the cars themselves. One example is emergency breaking. In case of an accident or if the brakes are pressed hard or floored, a notification is sent to following cars. Information of accidents can even be transported by cars driving in the opposite direction and, in this way, be conveyed to vehicles that might run into the accident. Other possible safety applications include passing assistance, security distance warning, and coordination of cars entering a lane [3, 4, 18]. Furthermore, sensors embedded in the car engine and elsewhere could be used for exchanging information, either with the onboard computer of the vehicle itself or with Higher-end vehicles with sophisticated computing and communication abilities, for diagnostic. This could facilitate preventive maintenance and minimizes road breakdowns.

Traffic monitoring and management systems

The conventional form of traffic monitoring systems is based on a centralized structure in which loop detector sensors and cameras along the roadside monitor traffic density and transmit the result to a central unit for further processing. Such systems are expensive and slow to react, require constant maintenance, and their widespread deployment has been hampered by the extremely large investment in the communication and sensor infrastructure that is required.

Alternative approaches based on vehicular ad hoc networking are currently being developed in several projects world-wide. In these approaches all vehicles are part of a ubiqitious sensor system. Each vehicle monitors the locally observed traffic situation, such as density and average speed, using onboard sensors and the results are transferred via wireless data-link through the network. A pilot project along these lines in Atlanta uses a fleet of 500 “traffic spies” equipped with onboard sensors, computer and GPS unit [23]. Other projects include Advanced Cruise-Assistant Highway Systems (AHS) and Vehicle information and Communication systems (VICS), FleetNet, AutoNet [9], and Path [10]. AHS assist at reducing traffic accidents, enhancing safety, improving transportation efficiency, and reducing the operational involvement of drivers. VICS allows drivers to obtain road and traffic information in real-time. FleetNet attempts to develop wireless multi-hop ad hoc networks for inter-vehicle communication to improve the driver's and passengers safety and comfort, and provide up-todate drivers with information on tarffic, weather and road condistions.

III. NETWORKING AND WIRELESS COMMUNICATION CHALLENGES

The environment in which vehicular sensor networks operate is extremely dynamic. For example, in highways *relative* velocities of up to 300 km/h can occur, and the density of nodes can vary from $1-2$ vehicles per kilometer in low density night traffic to more than 500 nodes/km in bumper-to-bumper traffic jam situations. Additionally, node densities can show large spatio-temporal variations due to dynamic traffic phenomena, such as platoon formation, and stop-and-go traffic jam waves [16]. Furthermore, whereas in low density situations a large transmission range is advantageous, in high density situations it can lead to a rapid drop in the capacity of the network due to contention and interference effects. Maintaining end-to-end (E2E) network connectivity, packet routing, timely and reliable information dissemination, and high speed wireless communication in such highly dynamic networks is extremely challenging.

E2E connectivity, routing and information dissemination

Regarding E2E network connectivity, the main issues are dealing with large inter-vehicle gaps in sparsely populated vehicular networks and the formation of isolated clusters of vehicles as a result of dynamic traffic conditions. One proposed solution is the introduction of infrastructure-based servers or gateways along the road which have a backbone interconnection to public or private network. Such gateways can act as bridges between isolated clusters of the vehicular networks. Another solution [12] is to use message relay boxes which store messages that they receive from vehicles and relay these later on.

In general, routing in a mobile ad hoc network is a challenging issue because of the network's dynamic topology changes. In vehicular ad hoc networks this problem is greatly amplified due to high node velocities involved, the highly dynamic patterns of mobility. Routing protocols for mobile ad hoc networks can be broadly divided into topology-based and position-based. Topology-based methods include pro-active methods based on distance vector or link state and reactive methods like dynamic source routing. In position-based routing each node is addressed by a unique identifier which contains information on the position of the node, e.g. its GPS coordinates. In order to forward a packet that contains a destination position, an intermediate node only has to be aware of its own position plus the position of a number of its one-hop neighbors. The intermediate node simply forwards the packet to a node closer to the destination than itself. The key feature of position-based routing is that, unlike in topology-based routing, neither route setup nor route maintenance are required. On the other hand position-based routing requires a system for dissemination and management of position information so that nodes can learn the current positions of their prospective communication partners. The results of recent simulation studies of routing in vehicular ad hoc networks suggests that position-based routing shows advantages over purely topology-based methods, in terms of adaptivity to changes of network topology and scalability [13].

In addition to routing, multi-hop forwarding (i.e. advancing a message along a roadway by transmitting the message from vehicle to vehicle) plays an important role in vehicular networks as it provides a simple yet robust method for information dissemination. For example, in traffic monitoring applications data packets containing information on velocity and local density could hop from car to car until they reach a vehicle close to an Internet gateway from where data can be transfered to the monitoring system [24]. Due to the broadcast nature of communication in vehicular networks nodes can receive the same forwarding packet multiple times, and have to contend with their neighbors for retransmission. For these reasons simple multi-hop forwarding of messages is highly inefficient and a number of algorithms have been put forward to improve this inefficiency. We are currently exploring epidemic (or gossip) routing protocols to improve the efficiency of message forwarding in vehicular ad hoc networks [14].

Wireless communication technology

Another important aspect of vehicular networks is the performance of wireless communication technology in vehicular mobility scenarios and various driving environments and conditions. Within the Traffimatics project extensive test scenarios were performed at BT Research to investigate the feasibility of using the IEEE 802.11 wireless LAN technology [6] for data transfer between moving vehicles and access points along the road. These experiments indicate that 802.11(b) works well in such scenarios, even when cars move at relatively high speeds. For example, it was possible to reliably transfer up to 40 Mb of data between a fixed access along the road point and a car moving passed it at a speed of 60 mph [19].

Inter-vehicle Wireless LAN performance have been investigated experimentally under various vehicular traffic mobility scenarios and environments (urban, suburban and highway). The network throughput and link quality were observed to decrease with increasing distance, as intuitively expected, and connectivity ranges of up to 1000 meters were found to be achievable, using enhanced antennas. On the whole, the IEEE 802.11 technology was seen to be suitable for inter-vehicle communication[22]. However, the results were obtained were for a network consisting of only two vehicles. It would be of great interest to see how these results will be modified in more realistic multi-vehicle settings, for example due to contention and interference effects.

Modeling vehicular mobility

Evaluating the performance of routing and information flow in vehicular ad hoc requires mobility models which capture the essential features of node movement in such networks. These movements are dictated by the highly complex phenomena of vehicular traffic [16], and cannot be described using available mobility models, such as random walk and random waypoint model.

Some of our current research at BT concerns devising and implementing realistic models of vehicular traffic. These mobility models are based on advanced car-following models of traffic dynamics. They implement vehicle-vehicle interactions and track the motion of individual vehicles. The model includes features such as individual vehicle characteristics, for example in order to distinguish between cars and trucks, and driver behaviors [15]. The implementation of these mobility models make it possible to simulate the dynamics of packet routing and information dissemination in vehicular networks in a variety of realistic traffic scenarios.

IV. DATA AGGREGATION, PROCESSING AND ANALYSIS: THE PROMISE OF VEHICULAR GRDIS

An exciting leap beyond the current traffic management systems will be *intelligent* traffic management systems. In such systems data collected from vehicular sensor networks will be fed into traffic analysis and simulation software for real-time detection and forecasting of undesirable traffic conditions, such as stop-and-go waves and congestion. The results are then used by the control system to dynamically adjust traffics conditions via lane and traffic signal control, ramp metering, cooperative driving, and traffic re-routing.

Such systems are currently still at an early stage and their development has been hampered by the inability of existing monitoring systems to deliver traffic flow data with sufficient spatial granularity and timeliness. With large-scale deployment of vehicular sensor networks, it can be expected that the data will become available in near future. However, when deployed on a global scale, the volume of data that vehicular sensor networks will generate will be vast, and its real-time aggregation and processing, as well as storage, can present a great computational challenge to existing systems. These types of problems can be addressed using computational grids. Grids [17] are distributed infrastructures that join together and coordinate vast amounts of computing resources in order to provide users with on-demand access to computing power, disk storage etc, and the integartion of wireless sensor networks with Grids has been considered very recently [25].

One suggested solution that makes use of some grid concepts, is to use a form of an autonomous and wireless vehicular Grid where vehicles play the role of both mobile sensors and mobile computers, and are linked together via wireless connections in order to act as grid computer on the road [26]. A high density of nodes in a segment of the road results in a higher density of potential nodes that can be temporarily organized on the fly to perform a distributed computing and solve a single problem. This network/computing capability can empower vehicle-driver safety applications. It is suggested that such a vehicular Grid can also be used to activate traffic control mechanisms, such as ramp metering.

Although the above architecture is very attractive because of its autonomous character and the fact that it harnesses the idle CPU cycles of in-vheicle computers, it has some major drawbacks. In particular, locally optimizing traffic flow in a stretch of road using the above system can result in the emergence of undesirable traffic conditions elsewhere in the road networks. We suggest, therefore, an alternative approach where intelligent traffic management is performed using a *global* traffic Grid system. This system will be fed contineously with sensor data from vehicular networks, and federates a pool of computing resources for aggregation, analysis and storage of the data, as well as real-time simulations, forecasting, and control of traffic flows. The abovementioend wireless vehicular grids can form one of the component in such a global traffic Grid, for example to provide some of the required computing power or for initial local processing and aggregation of sensor data.

V. CONCLUSIONS

Vehicular ad hoc networks provide an exciting area of research at the intersection of a number of disciplines and technologies. There is a plethora of future applications for VANET, ranging from diagnostic, safety tools, information services, and traffic monitoring and mangement to in-car digital entertainment and business services [1]. However, for these applications to become everyday reality an array of technological challenges need to be addressed.

In this paper we focused on sensor networks built on top of VANET and described a number of their applications. The networking and wireless communication challenges that such sensor systems are facing were reviewed, based partially on our own experience within the Traffimatics project, and some proposed solutions were reviewed. We described the application of vehicular sensor networks in future intelligent traffic management and control systems, and suggested an architecture for such systems in which vehicular sensor networks and vheicular wireless grids are integrated within a Grid for traffic monitoring, management and control.

ACKNOWLEDGEMENTS

We thank George Bilchev, Richard Gedge, Jane Tateson, Mikko Pasanen and Geir Freysson for discussions. Traffimatics is part of the Next Wave Technologies and Markets DTI Sponsored Programme.

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