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Keeping drivers together and vehicles apart – a systems approach to understanding the conflicts in VANET applications

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Abstract

This paper reviews a range of problems in the road transport field, and the potential role of the vehicular ad hoc network system (VANETs) in helping to solve them. In reality, the communications requirements vary widely from one application to the next, in terms of range, latency, and connectivity together with vehicle and roadside hardware. Applications that promise the greatest safety benefits will require relatively high market penetration together with governmental support. Much will therefore depend on the order in which successive applications are brought to market. Communications protocols that can easily be extended to take on more demanding applications at a later stage, and compatibility with existing systems such as electronic toll collection, will be important. The paper concludes with a brief assessment of the potential for VANET technology as a platform for a fully automated highway.

Introduction

There is no shortage of problems waiting to be tackled in the road traffic field. At first sight, the vehicular ad hoc wireless network (VANET) might appear as a universal solution, capable of improving safety, relieving congestion, and making travel more pleasant for passengers, all within a decade or so. In reality, though, traffic problems occur on different physical scales. For example, crash risks tend to be localised, while freeway congestion arises from travel demand at the city-wide or even state level. Moreover, some applications need to work very fast while others do not. The communications requirements vary widely one application to the next.

During the next few years, the first wave of VANET systems will be brought to market, largely aimed at services that drivers are willing to pay for. This first wave will greatly influence communications standards and protocols, and ideally, their design would allow for adaptation and expansion to cope with subsequent initiatives that tackle less commercial but equally important goals.

(Bai et al, 2006) have analysed 16 applications and allocated them to 7 groups. The applications were oriented towards on-board driver information and services. The aim of this paper is to extend the scope of applications at a strategic level, taking into account some of the fundamental problems faced by transportation engineers over a longer time scale. We also take into account two factors that will influence the way VANET systems are likely develop: (a) delay tolerance – in particular, the fact that some messages can usefully be transmitted several seconds after their content has been generated, and (b) market penetration, given that many applications require on-board hardware in

addition to the VANET equipment, and some cannot work at all unless all vehicles are so equipped.

Potential Applications

Potential applications are listed down the left-hand side of Table 1, grouped into four main areas. All are numbered to help identification. The terminology is not yet standardised, and in some cases, the application itself – what it is intended to achieve and how it might work - is still to be resolved. The following are not included in the table either because they could be regarded as sub-variants of the ones listed, or at present technically beyond reach, or likely to be carried out by other means:

- Roadside hardware fault-reporting
- Road surface condition monitoring
- CCTV surveillance
- Congestion management
- Overtaking assistance
- E-call (automated request for assistance in an emergency)
- Fuel payment at gas stations
- Freight and transit operations, e.g., consignment tracking, real-time information for passengers

Highway management. Highway management is expensive, and better data collection can significantly reduce costs. Nowadays, on-board sensors have the potential to turn every automobile equipped with GPS into a source of information about traffic flow conditions. Output from the first application in Table 1, *Floating car data*, can be used in two ways, firstly to support planning and maintenance, and secondly to provide on-line data input for route guidance and associated functions.

For brevity, the second item in the Table, *Electronic toll collection,* is taken to include parking payment and congestion charging, though existing implementations vary and there is no single communications model. In fact, as with *Floating car data*, all involve single-hop transmissions between the vehicle and a nearby roadside station, for which ad hoc network technology offers no particular advantage. However, it might be advantageous for these applications and other VANET applications ultimately to converge to a single, compatible communications framework.

In some countries, a small but growing proportion of drivers carry false license plates to escape detection for traffic or criminal offences. The license plate is often copied from that of a vehicle fitting a similar description, and this 'identity theft' is now causing serious difficulties for the police and the innocent victim. The UK government is being pressed to introduce an *Electronic vehicle and driver identification* system, probably in the form of an electronic tag built into every license plate. Roadside detector stations might usefully be supplemented by on-board VANET units among a proportion of the vehicle population, which would detect non-compliant vehicles out of range of the fixed roadside units. *Co-ordination of emergency service vehicles* involves the installation of OBU's in police cars, fire engines and ambulances to provide life-saving communications that could in principle involve the wider vehicle population.

Driver information. At their most basic level, *Autonomous congestion warnings* (item 5 in Table 1) can be derived from engine management and braking systems and relayed to vehicles upstream to warn of a traffic queue. Similarly, *Autonomous hazard warnings* can in principle be derived from the sensors fitted to most cars as standard. Alerts that can be passed on to other vehicles before they arrive at the scene include ice (triggered by the vehicle's ABS or Stability Enhancement System), and crash impact (triggered by airbag release), the presence of disabled vehicles, and the approach of emergency vehicles.

Advisory warnings of traffic regulations could be generated by local roadside transmitters and relayed from vehicle to vehicle to alert drivers to the presence of bus/HOV lanes together with turning, one-way and parking restrictions. A warning is more effective if it contains information from which the driver can form a mental picture of what lies ahead. *Centrally co-ordinated hazard warnings* refers to warnings with a descriptive content, such as weather alerts and road construction work zones together with

incidents such as breakdowns, crashes and load spills.

There have been several attempts to introduce *Dynamic route guidance* in which drivers can obtain information about traffic congestion in real time and switch routes accordingly. However, a high level of market penetration could lead to unstable oscillations in route choice, and other issues including the consequences of heavy traffic volumes switching to unsuitable routes remain to be resolved.

Sector	Application	Operating characteristics									Service standards						Hardware				
		Source and destination type		Service trigger			Target selection				Range		Maximum permissible end-to-end delay		Security		Minimum % of vehicles equipped with wireless units		Other hardware requirements		
		Vehicle-to-vehicle	Vehicle-to-infrastructure	Driver request	Generated by vehicle OBU	Externally generated	Untargeted open message	By relative position	By location	By identity	Local	Regional	Low	Delay-tolerant	Sensitive information	Safety-critical	Low	High	On-board GPS	Other on-board hardware	Roadside facility
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Highway management	1 Floating car data	■			■				■		■			■			■		■		■
	2 Electronic toll collection, parking payment and congestion charging (ETC)		■			■			■		■		■				■			■	■
	3 Electronic vehicle and driver identification (EVDI)		■			■	■						■	■	■		■			■	■
	4 Co-ordination of emergency service vehicles	■	■	■		■	■			■				■					■		
Driver information	5 Autonomous congestion warnings	■			■			■			■			■			■			■	
	6 Autonomous hazard warnings derived from vehicle sensors	■			■						■			■					■	■	
	7 Advisory warnings of traffic regulations		■			■			■				■	■			■		■		
	8 Centrally co-ordinated hazard warnings		■			■			■				■	■			■		■		
	9 Dynamic route guidance		■	■						■			■	■			■		■		
Traffic control	10 Chained cruise control	■			■			■			■		■					■		■	
	11 Collision avoidance at intersections		■		■			■			■		■			■		■		■	
	12 Automated ramp metering		■		■				■		■		■			■		■		■	
	13 Road trains	■			■			■			■		■			■		■		■	
	14 Intelligent Speed Adaptation (ISA)		■			■			■			■		■			■		■	■	■
On-board services	15 Driver-to-driver communication	■		■			■				■		■					■		■	
	16 Facilities guidance (Roadside kiosk)		■	■						■		■		■			■		■		
	17 Parking space reservation		■	■						■		■		■	■		■		■	■	
	18 Remote vehicle diagnostics		■	■	■					■		■		■	■		■		■		
	19 Internet connections		■	■						■		■		■	■		■		■		

Table 1. Communications requirements for a selection of potential VANET applications.

Traffic control. Traffic engineers try to reduce conflict between road users who are competing for limited road space. In principle, VANET technology permits co-ordination on a wider scale. We have coined the term *Chained cruise control* (item 10 in Table 1) to embrace various forms of cruise control and collision avoidance technology that until now have been marketed as autonomous driving aids. A 'chained' system would involve fast transmissions from vehicle to vehicle upstream to provide early warning of a shock wave or collision impact, and would provide valuable protection against multi-vehicle pile-ups on freeways, especially in bad weather.

Collision avoidance at intersections covers a variety of proposals including a roadside

unit that would monitor approaching vehicles at non-signalled junctions. VANET technology would allow the unit to allocate right-of-way by generating audio messages telling drivers to slow down or stop where necessary, or conceivably to over-ride the manual controls. Autonomous systems in which priority is negotiated directly among conflicting vehicles are also conceivable, subject to wireless range. Autonomous ramp metering at freeway access points is an obvious extension of this proposal.

Further off is the concept of *Road trains*, in which the communications model is similar to that for *Chained cruise control*, but control of each vehicle in a chain is actually handed over to the lead vehicle, so that all can travel at a higher speed and density than would otherwise be possible.

These last three applications are especially significant because they involve direct intervention in the 'conflicts' between vehicles that are associated with some of the most common – and most severe – types of crash. If they can be made to work, the safety benefits will probably outweigh those from any other VANET application. At the same time, a failure in any of these systems will be potentially catastrophic, so we shall refer to them as 'safety-critical'.

Intelligent speed adaptation essentially prevents drivers from breaking the speed limit, and could be extremely productive in terms of reducing both casualties and the costs of traffic enforcement (Carsten et al, 2005). A demonstration project has already been carried out in Sweden (Martin, 2002) using test vehicles equipped with GPS in combination with a digital map.

On-board services. Many of the systems mentioned so far require roadside infrastructure or other forms of public sector support. One of the attractions of using VANET technology is that some of the costs can be devolved to private vehicle users if possession of a unit offers access to services for which they are willing to pay. Such services include *Driver-to-driver communication*, (item 15 in Table 1) which, it has been suggested, could help to reduce road casualties by encouraging drivers to negotiate traffic 'conflicts' in a more co-operative fashion than they might otherwise do. In this instance, the technical problems are perhaps of less concern than the issue of privacy and how the system could be protected from abuse.

The next three items, *Facilities guidance (Roadside kiosk), Parking space reservation*, and *Remote vehicle diagnostics* are self-explanatory. *Internet connections* for email and web browsing can be provided via hotspots at service stations, truck stops, and retail store parking lots for example, and some analysts foresee VANET technology as a way of extending their range.

VANET Operations

A VANET system is not in itself a solution, but rather, an enabling technology or subsystem within an application that requires messages to be relayed among vehicles and between vehicles and roadside units. Key aspects of the way a VANET would work for each application are summarised in the left-hand block of columns in Table 1. The first two columns refer to the source and destination type. For obvious reasons, those that involve only vehicle-to-vehicle communication without the involvement of any roadside infrastructure are of particular interest to vehicle manufacturers. The remaining columns in this block deal with message handling: how the communications process is triggered (at least initially), and how the target or destination is identified. Both vary according to the application.

Service Trigger. Specifically, in columns 3 – 5, the Table refers to the source of the initial message that opens an exchange. There are three possibilities:

(a)   a vehicle passenger makes a request, for example for internet access

(b)   a signal is generated independently by the on-board unit (OBU), and

(c)   a signal is generated by a roadside unit.

Alternatively, as in (Bai et al, 2006), service triggers can be categorised according to the time at which they are generated: 'on demand', 'event-driven' (e.g., when the vehicle in question gets too close to the one in front), and 'beacon mode' (signals sent out at scheduled intervals). In principle, categories (b) and (c) above could be further subdivided in this way.

Target selection. Next we turn from the source of the message to its destination. For applications that involve two-way communication, the way the destination is targeted can vary from one phase of the exchange to the next. The targeting mode for the initial call is indicated in columns 6 - 9 of Table 1. In principle, there are four possibilities, of which the first, third and fourth correspond to what are more familiarly known to communications specialists as 'broadcast', 'geocast', and 'unicast' protocols respectively (Bai et al, 2006):

(a) Untargeted, open message
(b) Targeted by relative location,
(c) Targeted by absolute (geographical) location, and
(d) Targeted according to the identity of the vehicle or driver.

The first category applies to informal driver-to-driver conversation: the instigator's call can be heard by anyone who happens to be within range. Open calls may also be useful in an emergency, to identify and locate people such as off-duty doctors or police staff that might be available to help.

The second mode of targeting occurs in cases where the messages are used to control the interactions between vehicles in a moving traffic stream. For example, in a chained cruise control system, each vehicle sends messages to the one immediately behind, regardless of who is driving it, and where on the road system they happen to be at the time.

The third mode covers applications tied to specific road environment features: for example, hazard warnings. To avoid driver overload, delivery of warnings must be restricted to drivers within a narrow window of space and time. Hence a broadcast message must be filtered by the on-board unit, which suppresses the contents unless and until the vehicle happens to approach the hazard. An on-board GPS unit is required.

The last mode can be likened to telephone paging: the message is addressed to a particular individual or facility irrespective of whereabouts, which may or may not be known to the sender. Note that within this category, there are actually four distinct ways of identifying the 'target':

(a) a vehicle occupant
(b) the vehicle
(c) the OBU

(d) in cases where financial transactions are involved, the payee's credit account.

Another important consideration is how a message is routed to its destination. Many routing algorithms have been proposed (Li et al, 2002), (Chennikra-Varghese et al, 2006). Some are positional: the source must know its geographical location together with the location of the recipient, and uses that information to optimise the chain of relays to the target. Others are topological: they require advance knowledge of the way nodes are linked. Not all algorithms may be available for any given VANET application. For example, when a driver requests an internet connection, the routing of that request can only be topological, because the identity of the target is known but not its location on the network.

Service Requirements

What are the minimum service requirements and levels of infrastructure needed to make an application work? Key requirements are summarised in the remaining columns 10 – 20 of Table 1.

Range and connectivity. Almost half the applications are concerned with events occurring inside an area only a few hundred meters across, for example *Collision avoidance at intersections*. These localised applications require only single-hop transmissions between neighbouring vehicles or between a roadside station and vehicles passing by.

The remainder involve communications over much larger distances. Since gaps between vehicles of more than 400m occur on almost all roads at almost all times of the day, VANET systems as presently envisaged would be unable to deliver these services without roadside servers or gateways installed at regular intervals along each road, as proposed by (Nekovee, 2005). We shall take up this issue again later, noting for the time being that in some cases, for example, *Intelligent Speed Adaptation*, the number of stations could be reduced by arranging them in a cordon around the area concerned. The OBU's of entering vehicles would need to 'remember' the information and keep track of the vehicle's whereabouts on the network.

Maximum end-to-end delay. Protagonists often assume that, to be useful in road traffic, a VANET system must deliver information very quickly. But there are actually two distinct requirements. First, during any single 'hop' there may be a limited time window for the successful transfer of information packets to or from the vehicle, which is the case for most of the 19 applications listed. The time constraint is more severe for applications that involve large volumes of data such as internet connections and voice communications (Bai et al, 2006). The second requirement concerns end-to-end delay. For nearly half the applications (those that involve payment transactions at speed, traffic control applications that have to cope with rapidly changing dynamic relationships among vehicles on the road, and driver-to-driver communications) the overall delay must also be kept small, typically less than 0.2 ms for voice communications. However, for the remainder, latency is less critical: there may be quite long delays between hops.

Security. Applications that involve financial transactions or the transmission of sensitive information require a high level of protection from vandalism and sabotage. The same applies to the three safety-critical traffic control applications (items 11, 12 and 13 in Table 1), with the additional requirement that in the event of a failure of any kind, the system must be designed to shut down with minimal risk. Even a 'graceful' failure carries a significant penalty: vehicles would be brought to a halt, and - especially in the case of road trains - the failure could take a long time to disentangle. *Chained cruise control* is less vulnerable, because experience with earlier cruise control and collision avoidance systems has shown that they can be designed to revert to manual control in an emergency, so that a degree of malfunction does not necessarily entail a crash risk or lead to a traffic jam.

Hardware Requirements

Market penetration. Not unreasonably, commercial developers are focussing attention on applications that can be launched with initially low levels of market penetration, such as *Autonomous congestion warnings* (item 5). Assuming a sizeable traffic jam, there is a high probability of one or more messages being generated even if the proportion of vehicles equipped with OBU's is small. The pay-off for the individual user who chooses to buy the equipment is therefore not sensitive to total sales. Applications of this kind account for more than half the examples in Table 1 (see columns 16 and 17), although, in addition to a wireless transmitter / receiver, all require on-board hardware specific to the application such as a GPS unit, sensors, or a user interface, or some combination of these.

However, the position with regard to *Autonomous hazard warnings* (item 6) is less clear cut, for two reasons. First, only vehicles that are equipped with OBU's will be capable of generating a warning message, and if the proportion is small, most hazards will go unreported. Secondly, unlike delays, hazards often occur in sparse traffic: the warning signal broadcast by a vehicle that encounters an icy patch will not be relayed to the next vehicle on the scene if the distance between them exceeds wireless range. This leads to a conundrum for commercial developers. During the first year or so after launch, an equipped driver would not experience a reliable and consistent information flow. Hence there would be little incentive to buy the equipment.

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For applications capable of delivering large safety benefits such as *Chained cruise control*, a high proportion of vehicles

equipped with wireless units would be essential. The three safety-critical applications mentioned earlier require that all vehicles in the traffic stream are equipped and that the equipment is working. This is true also of *Electronic vehicle and driver identification* (item 3).

Message boxes. We can now return to the problem of limited range. For applications that require communication over long distances, how can a VANET system overcome the gaps that frequently occur even on busy roads? Fortunately, with one exception, none of the long-range applications requires high-speed transmission: in some cases they can tolerate end-to-end delays of several seconds or more. Consequently, gaps could be bridged by roadside 'message boxes' capable of storing information and relaying it to other vehicles arriving later, as proposed by (Reumerman et al 2005). But if the vehicle OBU's themselves were capable of storing incoming messages in RW memory, and relaying them to other vehicles when the opportunity arose, no roadside units would be needed. After it had first been injected into the traffic stream, a message would be propagated both upstream and downstream roughly at the average speed of traffic in those directions.

Implementation

We can now examine the communications requirements to see which applications have similar profiles. We shall focus on just three of the requirements: range, end-to-end delay, and market penetration. In Figure 1, they are represented by the three perpendicular axes of a graph, except that the criterion 'end-to-end delay' has been replaced by its notional inverse 'speed'. Each of the potential traffic applications can be represented by a point in this three-dimensional space. The further away from the origin, the more stringent the requirements, hence an application lying close to the origin would be relatively easy to implement, while an application at the corner of the cube diagonally opposite the origin would be relatively demanding.

Individual applications are not shown in the diagram, but one can identify three important clusters that between them account for 16 of the 19 listed in Table 1. The first

cluster, indicated by the green disk at the origin, contains the two applications that are the least demanding in terms of speed, range, and market penetration: *Floating car data* and *Autonomous congestion warnings*. The largest cluster (9 applications), indicated in yellow at the bottom of the diagram, is made up largely of information services that do not involve real-time voice communications or financial transactions. All are to some extent delay-tolerant and none rely on high market penetration: the key requirement is range. The third cluster, indicated in red, represents the three 'safety-critical' applications together with *Chained cruise control* and *Driver communications*.
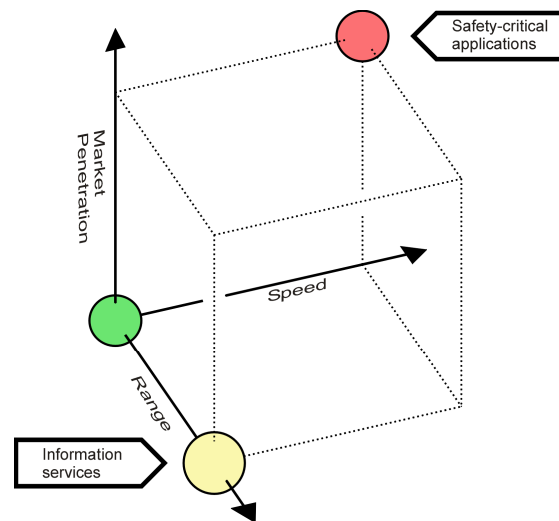

Figure 1. Communications requirements for different transport applications.

The evolving market. There is now a great deal of competition to bring applications to market, and it would be useful to visualise a sequence of development that might accommodate them all. In Figure 2, the grey arrows are intended to show how the simplest and most straightforward applications might lead to more complex and more challenging ones, against a background of gradually increasing market penetration of OBU's.

Starting at the top of the diagram, the first applications are likely to be

  (a) commercially-driven

  (b) autonomous

  (c) not easily achievable with alternative communications technology, and

(d) undemanding in terms of range, speed, and dependence on market penetration.

Only one application meets all these criteria: *Autonomous congestion warnings*.

Autonomous hazard warnings, Chained cruise control, and *Driver-to-driver communications* could join at a later stage if supported by high market penetration.
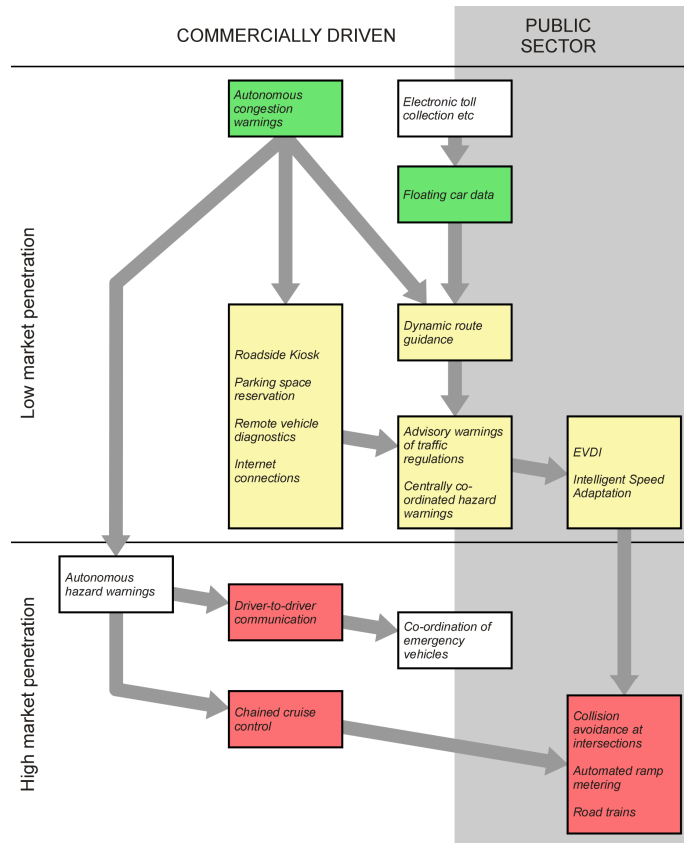

Figure 2. The evolution of VANET applications – a possible sequence.

If we drop the 'autonomous' requirement, next in line would be *Electronic toll collection*, which only requires a single-hop transmission. A VANET implementation, however, would need to demonstrate considerable advantages over existing DSRC technology.

A third tranche of applications can be brought into play with the addition of a message box facility incorporated within each wireless unit to overcome the range problem. These are the long-range driver information services that require neither high market penetration nor high-speed communications, located among the 'yellow' group in Figure 1: *Advisory warnings of traffic regulations, Centrally co-ordinated hazard warnings,*

Dynamic route guidance, Roadside kiosk, Parking space reservation, Remote vehicle diagnostics, and *Internet connections*. Although commercially driven, some would need public-sector input in the form of traffic or network data that is normally maintained by the highways agency concerned.

All of the remaining applications would need to be driven by the public sector. *Floating car data* is technically undemanding and could yield significant benefits to a highway agency with relative modest infrastructure investment. *EVDI* and *Intelligent speed adaptation* are technically within reach but politically controversial. Probably the most difficult challenges lie with *Collision avoidance at intersections,*

Automated ramp metering, and *Road trains.* These three are likely to yield the most significant safety benefits of all the applications considered in this paper, but they raise difficult legal issues, and they would involve substantial public funding together with a long development period and retro-fitting of OBUs to all road-going vehicles.

This leaves just one application not accounted for: *Coordination of* e*mergency service vehicles.* Surprisingly, this has been cited as one of prime candidates, but the need for high-speed voice communication over long distances could not be met without a dense network of roadside stations. On the other hand, emergency vehicles could use VANET technology in single-hop mode as a means of warning other vehicles of their approach.

Standards. Applications based on VANET technology are now being developed by consortia in many different countries, and at the same time, research is being conducted by government-funded agencies (ITS in the USA, and, under the banner *eSafety*, the European Commission in Europe) to define common standards for vehicular communications so that the various applications are compatible. The main initiatives include standards definition for

- physical and link layers
- frequency allocation
- routing algorithms
- security requirements.

As currently envisaged by the US Department of Transportation in its National Architecture for Intelligent Transportation Systems (ITS), DSRC (Dedicated Short Range Communications) is intended to provide very high data transfer rates in circumstances where minimizing latency in the communication link and isolating relatively small communication zones are important. This includes vehicle-to-vehicle and vehicle-to-infrastructure communication. It is a general purpose radio frequency integration technology (RFIT) and it works on the 5.9 GHz band in the U.S. (5.8 GHz in Europe and Japan) with a bandwidth of 75MHz and approximate range of 1000m (US Department Of Transportation, 2003).

The DSRC standard does not allow for the formation of ad hoc networks. The system provides a control channel together with six service channels. Each roadside unit operates independently, using the control channel to send out beacon signals announcing the applications it supports, and also to broadcast safety messages. The signals are monitored continuously by OBU's which switch to the appropriate service channel to send and receive messages.

So far, DSRC has been used mainly for applications that involve financial transactions such as *Electronic Toll Collection*, for which implementations exist in Europe, Japan and the USA. These systems are not at present compatible. Similar applications include payment for parking facilities, payment for fuel in gas stations, and congestion charging in city centers. Other DSRC applications include weather and traffic data collection, traveller and road information, safety alerts, hazardous freight consignment tracking and intelligent speed adaptation. Most of these use proprietary technology, although some standards-compliant devices have been developed.

A second set of standards is being developed within the IEEE 802.11 family. Wireless Access in the Vehicular Environment (WAVE), allows for the formation of ad hoc networks and is specifically tailored to ITS applications where transactions must be completed much more quickly than is possible with DSRC (Cash, 2008). Used as the groundwork for DSRC, WAVE defines enhancements to 802.11 required to support ITS applications. This includes data exchange between vehicles and between these vehicles and the roadside infrastructure in the licensed ITS band of 5.9 GHz (5.85-5.925 GHz).

DSRC typically operates in the physical and link level layers 1 and 2 of the protocol stack, whereas WAVE operates in the remaining layers 3-7 (network, transport, session, presentation and application layers) (National Highway Traffic Safety Administration, 2006). The integration of both these standards applied to the entire protocol stack is called DSRC/WAVE, and it is this integrated standard that forms the basis of the U.S. Department of Transportation's Vehicle Infrastructure Integration (VII) vehicle-based communication networks project. The vision is to develop a nationwide network that enables communications between vehicles and roadside access points or other vehicles.

Conclusion

We have suggested that different applications are likely to make very different demands on a VANET system. If each problem were tackled in isolation, the solutions in terms of wireless technology would probably be different. This does not necessarily mean that the vision of a single VANET solution is wrong. But it does mean that the order in which successive applications reach the marketplace could be important, and that the service specification should allow for upgrading and compatibility with other forms of communication technology. Integral message boxes could pave the way for a potentially large number of information services that are delay-tolerant but need to transmit over relatively long distances.

Looking further ahead, two major revolutions are approaching: first, cars will become capable of driving themselves, and we suspect that unlike its DARPA predecessors, the 'robot car' will be anything but autonomous - it will need to share information. The safety benefits alone will far outweigh anything the highway engineer can achieve with conventional road improvements, but at the same time, if successful, the demand for road space could escalate well beyond today's levels as a new generation of passengers begins to take advantage of stress-free travel over longer distances. Secondly, in order to cope with the pressure, piecemeal traffic control systems will inevitably merge, and a powerful multi-purpose communications system will be needed to glue the applications together into a common framework. Clearly, it would be helpful to envisage and plan an effective and affordable pathway to implementation, around a common communications standard.

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