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Published in:
IEEE Communications Surveys and Tutorials

2008

2ND QUARTER 2008, VOLUME 10, NO. 2

IEEE COMMUNICATIONS SURVEYS

www.comsoc.org/pubs/surveys

INTER-VEHICLE COMMUNICATION SYSTEMS: A SURVEY

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ABSTRACT

Inter-vehicle communication (IVC) systems (i.e., systems not relying on roadside infrastructure) have the potential to radically improve the safety, efficiency, and comfort of everyday road travel. Their main advantage is that they bypass the need for expensive infrastructure; their major drawback is the comparatively complex networking protocols and the need for significant penetration before their applications can become effective. In this article we present several major classes of applications and the types of services they require from an underlying network. We then proceed to analyze existing networking protocols in a bottom-up fashion, from the physical to the transport layers, as well as security aspects related to IVC systems. We conclude the article by presenting several projects related to IVC as well as a review of common performance evaluation techniques for IVC systems.

Vehicular transportation is, and will remain, one of the main modes of transportation for millions of U.S. citizens (and hundreds of millions around the world) in spite of increasing oil prices and environmental concerns. However, 38,252 Americans were killed in 2003 with 2,697,000 seriously injured [1, 2]. Furthermore, each day the average American spends 2.5 hours in his/her vehicle, a significant percentage of this time in traffic jams and at stop lights. The statistics are similar in many other parts of the world. Vehicular communication systems that can transmit and receive information to and from individual vehicles have the potential to significantly increase the safety of vehicular transportation and improve traffic flow on congested roads.

Inter-vehicle communication systems (IVCs) rely on direct communication between vehicles to satisfy the communication needs of a large class of applications (e.g., collision avoidance, passing assistance, and platooning). IVC systems can be supplemented or, in some situations, replaced by roadside infrastructure, allowing for Internet access and several other applications. A more detailed discussion on the classification of vehicular communication systems is presented. This article is focused on pure IVC systems without roadside assistance. Recently the term vehicular ad hoc network (VANET) was introduced for multihop networks of vehicles not relying on roadside infrastructure. We chose to use the term IVC as it is more general, including single-hop networks. Furthermore, the term IVC is extensively used in the existing literature. A brief survey on IVC systems [3] focuses on medium access control (MAC) and routing issues, in particular pointing to the mismatch between the need of IVC applications for group communications and the services offered by mobile ad hoc network (MANET) routing protocols.

We classify several applications enabled by vehicular communication systems. Understandably, the most commonly considered applications are related to public safety and traffic coordination. Traffic management applications, traveler information support, and various comfort applications have the potential to make travel (considerably) more efficient, convenient and pleasant. For each type of application we consider its addressing and real-time requirements, and the type of vehicular communication necessary for its implementation.

We then survey existing solutions at each networking layer, from physical to transport, including security issues. We contrast the existing solutions while exposing their advantages and drawbacks. Due to the significant technical and logistical difficulties involved in deploying large IVC testbeds, the vast majority of the proposed solutions are evaluated using simulations or small testbeds. We also survey the road and wireless channel models, traffic and network simulators, as well as prototypes used to evaluate the performance of the proposed system designs. Throughout the article we present results from previous experiments with prototypes.

Much of the published research in this area is based on oversimplified models. The gap between simulation and reali-

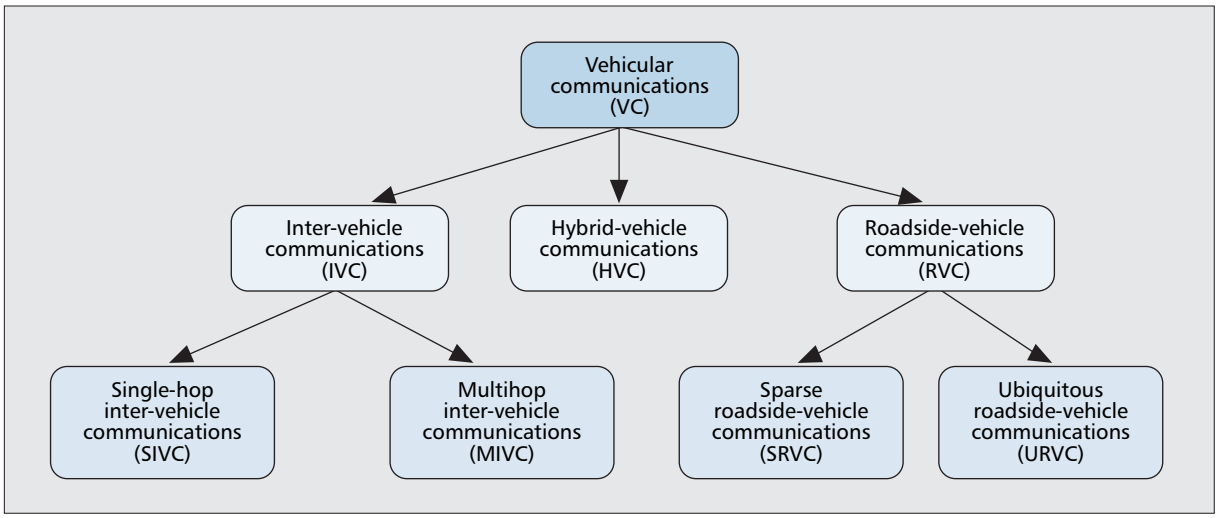


Figure 1. *A taxonomy of vehicular communication systems.*

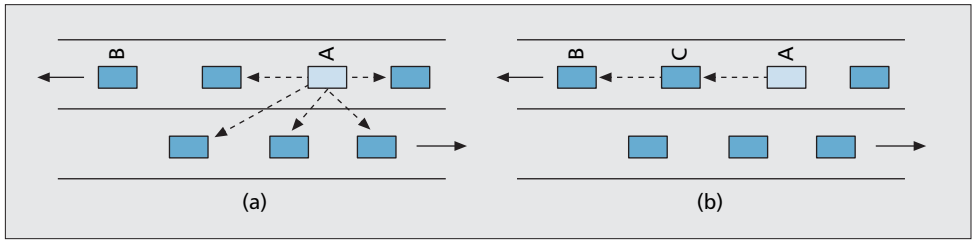


Figure 2. *a) Single-hop; b) multihop IVC systems.*

ty strongly shows the need for field trials [4]. Finally, we present several projects related to vehicular communication systems and conclude the article.

Background

IVC systems have been an active research area for over two decades. In this section we provide a brief overview of the pioneering work in this area. The early research was focused mostly on short-range communication systems, only considering single-hop data transfers. The main objective of the papers was to solve the problem of data transmission between two moving vehicles. Multihop systems were not considered at the time. Wireless LAN techniques were not yet standardized; therefore, many different solutions were proposed. In applications like cooperative driving it is crucial that a vehicle has exact knowledge of the location of its neighbors. Since GPS was not widely deployed during the early projects (or did not offer sufficient precision), a significant effort was dedicated to determining the exact location of the vehicles and the distance between them [5].

A number of solutions for the physical layer were proposed and evaluated. Several early papers proposed various optical solutions, using a laser beam for both data transfer and measuring the distance between vehicles [6]. Other papers investigated different spread spectrum techniques [7]. A new transmission system called Boomerang was proposed and evaluated [8]. Boomerang is based on direct sequence spread spectrum (DSSS) and focused on the problem of assigning spreading sequences to the vehicles.

At the MAC layer, many papers proposed various slotted solutions. Different versions of the slotted ALOHA scheme were proposed [9]. Others proposed various time-division schemes [10]. A major problem in slotted schemes is the need for exact synchronization. In [11] a new MAC protocol called COCAIN was proposed that worked without slots and reservations. COCAIN had similarities with the carrier sense multiple access (CSMA) scheme used in IEEE 802.11, but, understandably, did not catch on.

Not many projects at the time were focusing on any specific applications. The PATH project [12] considered the control problems related to cooperative driving and vehicle platooning.

Most papers mentioned above were published before the wide deployment of the Internet, wireless LANs, and GPS. Therefore, the proposed IVC solutions may not be relevant today. However, they are important in understanding the background of IVC systems. In the rest of the article we consider publications based on current communication technology (i.e., cellular networks, wireless LANs, and GPS).

Taxonomy and Assumptions

Figure 1 depicts a classification of vehicular communication (VC) systems. There are three major types of systems: IVC systems, roadside-to-vehicle communication (RVC) systems, and hybrid vehicular communication (HVC) systems. In this survey we focus on pure IVC systems (i.e., without roadside equipment); however, when suitable, we make reference to other types of VC systems.

Inter-Vehicular Communication Systems

IVC systems are completely infrastructure-free; only onboard units (OBUs) sometimes also called in-vehicle equipment (IVE) are needed. IVC systems are the main focus of this article. Depending on whether the information is retransmitted at intermediate hops or not, we can further distinguish

between single-hop and multihop IVCs (SIVCs and MIVCs). SIVC systems are useful for applications requiring short-range communications (e.g., lane merging, automatic cruise control). MIVC systems are more complex than SIVCs but can also support applications that require long-range communications (e.g., traffic monitoring).

The main difference between SIVC and MIVC systems is shown in Fig. 2. In an SIVC system vehicle A can send a message only to the cars that are in its transmission range (i.e., vehicle B never receives the message). On the other hand, in an MIVC system another vehicle (vehicle C in Fig. 2b) can relay the message such that vehicles not in the transmission range of vehicle A (e.g., vehicle B) can also receive the message. Therefore, an MIVC system requires a network layer capable of multihop routing.

Roadside-to-Vehicle Communication Systems — RVC systems assume that all communications take place between roadside infrastructure (including roadside units [RSUs]) and OBUs. Depending on the application, two different types of infrastructure can be distinguished, sparse RVC (SRVC) and ubiquitous RVC (URVC) systems.

SRVC systems are capable of providing communication services at hot spots. A busy intersection scheduling its traffic light, a gas station advertising its existence (and prices), and parking availability at an airport, are examples of applications requiring an SRVC system.

An SRVC system can be deployed gradually, thus not requiring substantial investments before any available benefits. A URVC system is the holy grail of vehicular communication: providing all roads with high-speed communication would enable applications unavailable with any of the other systems. Unfortunately, a URVC system may require considerable investments for providing full (even significant) coverage of existing roadways (especially in large countries like the United States).

Hybrid Vehicular Communication Systems

HVC systems are proposed in the literature for extending the range of RVC systems. In HVC systems vehicles communicate with roadside infrastructure even when they are not in direct wireless range by using other vehicles as mobile routers. An HVC system enables the same applications as an RVC system with a larger transmission range. The main advantage is that it requires less roadside infrastructure. However, one disadvantage is that network connectivity may not be guaranteed in scenarios with low vehicle density.

IVCs vs. MANETs

MANETs [13] are wireless multihop networks that lack infrastructure, and are decentralized and self-organizing. IVC systems satisfy all these requirements, and are therefore a special class of MANETs. However, there are several characteristics that differentiate IVCs from the common assumptions made in the MANET literature:

- **Applications**. While most MANET articles do not address specific applications, the common assumption in MANET literature is that MANET applications are identical (or similar) to those enabled by the Internet. In contrast, as we show later, IVCs have completely different applications. An important consequence of the difference in the applications is the difference in the addressing modes.
- **Addressing**. Faithful to the Internet model, MANET applications require point-to-point (unicast) with fixed addressing; that is, the recipient of a message is another node in the network specified by its IP address. However, IVC applications often require dissemination of the messages to many nodes (multicast) that satisfy some geographical constraints and possibly other criteria (e.g., direction of movement). As pointed out in [3], the need for this addressing mode requires a significantly different routing paradigm.
- **Rate of Link Changes**. In MANETs the nodes are assumed to have *moderate* mobility. This assumption allows MANET routing protocols (e.g., Ad Hoc On Demand Distance Vector, AODV [14]) to establish end-to-end paths that are valid for a reasonable amount of time and only occasionally need repairs. In IVC applications it is shown that due to the high degree of mobility of the nodes involved, even multihop paths that only use nodes moving in the same direction on a highway have a lifetime comparable to the time needed to discover the path [15].
- **Mobility Model**. In MANETs, the random waypoint (RWP) [16] is (by far) the most commonly employed mobility model. However, for IVC systems, most existing literature recognized that RWP would be a very poor approximation of real vehicular mobility; instead, detailed vehicular traffic simulators are used [17, 18].
- **Energy Efficiency**. While in MANETs a significant body of literature is concerned with power-efficient protocols, IVC enjoys a practically unlimited power supply.

Assumptions

Regardless of the type of VC, some form of OBU is necessary. Following is a list of hardware that most papers assume available in each *equipped* vehicle:

- A central processing unit (CPU) that implements the applications and communication protocols;
- A wireless transceiver that transmits and receives data to/from the neighboring vehicles and roadside;
- A GPS receiver [19] that provides relatively accurate positioning and time synchronization information;
- Appropriate sensors to measure the various parameters that have to be measured and eventually transmitted;
- An input/output interface that allows human interaction with the system.

Realistically, only a few vehicles will be equipped initially.

Applications

In this section we present an overview of several applications enabled by vehicular communication systems. The considered applications are not meant to be comprehensive, but rather representative of major classes of applications. Good overviews of applications can also be found in [20, 21].

For each considered application class we consider the type of vehicular communication system (IVC, RVC, etc.) required for its implementation, system penetration, addressing mode, as well as real-time requirements.

As far as applications are concerned, two addressing schemes have been commonly considered in wireless ad hoc networks [13]:

- **Fixed** addressing where each node has a fixed address assigned by some mechanism at the moment it joins the network; the node uses this address while it is part of the network. This is the most common addressing scheme in the Internet (with mobile IP being the exception). Most ad hoc networking applications and protocols assume a fixed addressing scheme.

- **Geographical** addressing where each node is characterized by its geographical position. As the node moves, its address changes. Additional attributes may be used to further select a subset of target vehicles. Examples of such attributes are:
  –The direction of movement of the vehicle,
  –The road identifier (e.g., number, name),
  –The type of vehicle (trucks, 18 wheelers, etc.),
  –Some physical characteristics (e.g., taller than, weighing more than, or at a speed higher than),
  –Some characteristic of the driver (beginner, professional, etc.).

Several other addressing schemes have been considered in the wireless networking literature (e.g., topological and attribute-based addressing), but we believe that they are not particularly relevant for VC systems.

We consider addressing options from the network layer's perspective and present mapping strategies from one address space to the other.

Public Safety Applications

Public safety applications are geared primarily toward avoiding accidents and loss of life of the occupants of vehicles [22–24]. Collision warning systems have the potential to reduce the number of vehicle collisions in several scenarios.

On highways, frontal collisions with slow moving (or stopped) vehicles are one of the most common types of accidents, often with serious consequences. A vehicle with its airbags deployed, or a stopped or rapidly decelerating vehicle can transmit warning signals to all other approaching vehicles. Intermediate relays may be used to increase the dissemination range of the warning beyond the direct transmission range.

At intersections, vehicles running red stop lights often result in side crashes [25]. If both vehicles to be involved in the accident are equipped with vehicular communication systems, such accidents can be prevented. A similar situation may occur with other types of vehicles (e.g., trains) [25].

In some cases, if a collision is imminent, the system may be able to prepare the vehicles for collision (inflate air bags, tighten seat belts, etc.) [25].

Safety applications have obvious real-time constraints, as drivers have to be notified before the information is no longer useful. Either an MIVC or a URVC (SRVC for intersections) can be used for these applications. It is possible that, depending on the communication range, an SIVC may be sufficient for these applications.

However, the system penetration will have a direct influence on the usability of the system: in a system with p percent penetration, a vehicle equipped with such a system will benefit in p percent of the situations.

In terms of addressing, the destinations in these applications will not be individual vehicles, but rather *any relevant* vehicle. The zone of relevance (ZOR) (also known as the target area) is determined by the particular application. For example, an accident in the right lane of a highway will only affect vehicles approaching the accident from behind [22], while at an intersection the vehicles with intersecting trajectories and speeds over a threshold are relevant.

Traffic Management Applications

Traffic management applications are focused on improving traffic flow, thus reducing both congestion as well as accidents resulting from congestion, and reducing travel time [26–29].

Traffic monitoring can provide high-resolution localized timely information regarding the traffic for several miles around the current location of the vehicle. For this application each vehicle in the system will act as a sensor (determining its current speed), as a relay (if the information is to travel for more than the direct transmission range) as well as a destination (using information from the other vehicles in the system). The information can be used to simply inform the driver or, in more complex systems, to reroute, estimate the time to destination, or even control the traffic by using adaptive speed limits, ramp metering, and so on.

Traffic light scheduling can be significantly improved by using an SRVC system. Currently, many traffic lights are scheduled either statically or only considering limited information (e.g., by sensing the presence or absence of a vehicle in front of a traffic light). An SRVC system can provide additional information, such as the length of the queues at the traffic light as well as the number of vehicles expected to arrive in the near future, which can improve the efficiency of schedules.

Emergency vehicles may notify the relevant vehicles as well as equipped stop lights of their presence and intended routes.

Applications in this class generally do not have stringent real-time requirements: the quality of the information degrades gracefully with the increase of delay and packet loss.

Similar to the case of safety applications, the destinations of the information are any vehicles in the ZOR. For traffic monitoring applications the ZOR can be several miles around the information source. For traffic light scheduling, traffic lights being approached are appropriate destinations.

Traffic Coordination and Assistance Applications

Traffic coordination and traffic assistance have been the main research topics of many IVC projects [30–32].

Platooning (i.e., forming tight columns of vehicles closely following each other on highways) has the potential to radically increase the capacity of existing highways. High-speed closed loop control is of paramount importance for this application.

Passing and lane change assistance may reduce or eliminate risks during these maneuvers, since they are often the source of serious accidents.

Clearly these applications require close-range IVC with tight real-time constraints and can be implemented with either an SIVC or a URVC system. Both systems can offer similar real-time guarantees and delays if properly designed, although an SIVC system may have a slight advantage as it faces reduced contention and direct links.

These applications also have addressing based on ZOR; for example, immediately behind, in the right lane, or in the reverse direction. Penetration directly influences the usability of these systems.

Traveler Information Support

Traveler information support applications provide updated local information, maps, and in general messages of relevance limited in space and/or time.

Local information such as local updated maps, the location of gas stations, parking areas, and schedules of local museums can be downloaded from selected infrastructure places or from other "local" vehicles. Advertisements with, for example, gas or hamburger prices may be sent to approaching vehicles.

Road warnings of many types (e.g., ice, oil, or water on the road, low bridges, or bumps) may easily be deployed by authorities simply by dropping a beacon in the relevant area.

Only a few papers consider specific traveler information support applications [29,33]. All information support applica-

Application	Can be implemented with				Addressing mode	OBU penetration dependent	Real-time requirements
	SIVC	MIVC	SRVC	URVC			
Collision warning (highway)		√		√	Geo	√	√
Collision warning (intersection)	√	√	√	√	Geo	√	√
Traffic monitoring		√		√	Geo	√	
Traffic light scheduling			√	√	Geo	√	
Traffic coordination	√	√		√	Geo	√	√
Traveler information support			√	√	Geo		
Targeted vehicular communications	√	√		√	Fixed	√	
Car to land communications				√	Fixed		

Table 1. *Summary of application requirements and characteristics.*

tions require an SRVC system. IVC systems may augment the service provided by the SRVC, but cannot replace it. No special real-time requirements are necessary, and the penetration percentage has no impact on usability. A vehicle equipped with a vehicle communication system benefits from the applications independent of the OBU penetration rate. The addressing is once again based on relevance rather than individual vehicle IDs.

Comfort Applications

The main focus of comfort applications is to make travel more pleasant [34, 35]. This class of applications may be motivated by the desire of passengers to communicate with either other vehicles or ground-based destinations such as Internet hosts or the public service telephone network (PSTN).

Targeted vehicular communications allow *localized* communications (potentially multihop) between two vehicles. Voice, instant messaging, or similar communications may occur between the occupants of vehicle caravans traveling together for long distances, or between law enforcement vehicles and their "victims." Note that this application does not scale to large network sizes.

Vehicle to land-based destination communications is arguably a very useful capability as it may enable an entire array of applications, from email and media streaming to Web browsing and voice over IP. Unfortunately, land-based access *requires* a URVC system that may be prohibitively expensive in the near future.

Finally, there are many other comfort applications. *Tolls* for roads and bridges can be collected automatically. Many nonstandard systems exist and work well. *Parking* payments can be made promptly and conveniently. *Repair and maintenance* records can be recorded at the garages performing them. Multimedia files such as DVDs, music, news, audiobooks, pre-recorded shows can be uploaded to the car's entertainment system while the car is in the garage.

Vehicle-to-vehicle communications may be implemented using either an IVC or a URVC system. All communication applications use individual addressing rather than geographical, and, except for multihop targeted vehicular communications, have usability independent of penetration rate. The other comfort applications can be enabled by an SRVC system with individual addressing and have usage independent of the penetration rate.

Summary

Table 1 summarizes the characteristics and requirements of the applications considered in this section. The envisioned IVC applications have very different characteristics and requirements. Diverse solutions have been proposed at the lower layers to fulfill these requirements. Consequently, no clear application-layer interface (similar to TCP/IP sockets) have been proposed for writing applications for IVC systems.

Short-Range Communication Technologies

Some applications, for example cooperative driving, requires a very short-range communication, possibly with line-of-sight. For these types of applications only a physical and perhaps a simple MAC layer are needed. Several papers have designed and proposed various physical layers for this type of applications.

The solutions presented in this section have not been evaluated for multihop systems. Most often, the papers in this category have only focused on the physical layer, without considering how this layer can be incorporated into the networking stack.

Communication Technologies

Many of the proposed automatic cruise control systems are based on radar range measurements in the 60 GHz band. Naturally, several papers propose to also use the radars for communication [36], and consider problems ranging from modulation techniques [37] to propagation models [38, 39] and antenna design [40]. Given the frequency band, these systems work best with line of sight between the transmitter and the receiver, which means that only very short range communication can be obtained. Mirrors may be used to "see" around corners [41] in low-visibility intersections. This limitation is especially important in the initial phases of the system's deployment when the penetration will be low.

Ultra-wideband communication systems [42] have very good ranging capability, and for short distances the potential for very high data rates. Several issues ranging from waveform selection [43] to modulation techniques and ranging capabilities [44] are studied in the context of IVC. However, there is

still a need for much more research on this subject. Given the current power limitations imposed by the FCC [45], the direct transmission range is limited to a few meters (tens of meters if low data rates are tolerated), thus reducing the applicability of these systems.

Optical communication systems, including lasers and infrared, are especially well suited for direct line of sight and relatively short communication, thus being suitable for SIVC systems [46]. MIVC systems can be also constructed on an optical physical layer [47]. Similar to the case of millimeter wave and UWB, optical communications can be used for ranging, thus being especially useful for traffic coordination applications, but are of limited use for other applications.

All three communication technologies have good potential for short-range communications, although many details are left out in the mainly theoretical papers (except for [37], which describes a benchtop testbed). An important advantage of all three technologies is that they all can provide ranging in addition to communications. The main disadvantage is their relatively short range.

Experiments

Coordinated driving and vehicle platooning have been the focus of many research projects. These applications have also been tested in a number of experiments using short-range communication. In this section we discuss a couple of these experiments.

The PATH project involved an experiment on cooperative driving [30]. The experiment included eight cars, driving in a platoon at highway speeds. The objective of the experiment was to compare the performance of a cooperative longitudinal control system using IVC with the performance of a constant time gap autonomous control system using radar. With the cooperative control system, an intervehicle spacing of 6.5 m was successfully maintained.

At Honda's test site, five vehicles platoon formation were used in an experiment [48]. The system was based on laser radar sensing and IVC. The researchers used four automatically operated test vehicles following a manually operated lead vehicle at maximum speeds of 100 km/h, with 4 m intervehicle spacing.

The results of the above experiments are impressive. However, the control systems coordinating the vehicles are dependent on fast feedback using line-of-sight radar. The focus of these experiments is on the control system rather than communication. A considerable effort is required to achieve similar performance with a system using a general-purpose networking stack due to the unpredictable (or at least less predictable) delays involved in such a system.

In [49] an experiment with vehicle platooning is described. The system uses an industrial, scientific, and medical (ISM) band RF transceiver and a simple medium access control (MAC) protocol. The system is implemented on three scale vehicles and uses one remote control station that coordinates the communication. Very short sampling intervals (30 ms) are required for the system to work. Therefore, more research is needed on designing a control system to coordinate driving based on a general-purpose network protocol stack.

Network Access

Network access in the Internet includes the physical and data link layers of the OSI model [50]. Since wireless communications are inherently broadcast, a MAC layer has to be implemented in practically all IVC systems. In IVC systems fast and slow fading effects can be expected to cause problems as both the transmitter and receiver are moving, potentially toward each other. Also, the antennas of both the transmitter and receiver are closer to the ground than the typical cellular base station.

Today, there are several communication standards that may be used as access networks for IVC systems, such as Bluetooth, IEEE 802.11, and cellular mobile networks (e.g., GSM, GPRS, and 3G). All these standards have advantages and disadvantages depending on the type of application and considered scenario.

Many new medium access protocols have been proposed specifically for IVC systems. A few of them are presented later; however, standardization of new MAC protocols is usually a lengthy process, and we expect that the first commercial systems will use one of the already existing access technologies.

Also, it is possible that an IVC system could support several access technologies, as proposed in [51]. The author of [51] envisions a gateway architecture such that the communication within the IVC system can use different access networks. However, the architecture in [51] relies on fixed addressing and presents no performance evaluation of the proposed architecture, thus inviting more research on the subject.

IEEE 802.11 and DSRC

IEEE 802.11 [52] is currently the most widely used wireless local area network standard in the world. Due to its widespread use, the price of this relatively high-performance equipment is very low, making it the hardware of choice for IVC testbeds on shoestring budgets. The 802.11 MAC layer is implemented in practically all network simulators, making the evaluation of the performance of IVC systems based on 802.11 hardware relatively easy.

Recently, a dedicated short-range communication (DSRC) standard for vehicular communications was approved by ASTM International and is now following the standardization process in IEEE [25]. The MAC layer, frequency band, and modulation of DSRC is very similar to those of 802.11a [53].

Therefore, it should come to no surprise that 802.11 and DSRC are the MAC layers most commonly assumed in IVC systems. Many researchers use 802.11a models to evaluate the performance of 5.9 GHz DSRC systems. References [24, 54] present physical and MAC layer models and highlight the advantages as some of the possible pitfalls of a 5.9 GHz DSRC system. Small-scale testbed experiments [55, 56] in 2.4 GHz show that an 802.11 scheme works well on distances between 100 and 1000 m depending on the modulation used, road characteristics (curves, raised bridge, etc.), and transmission power.

Several classes of applications based on a DSRC access network have been considered: traffic monitoring [26, 27, 29], collision avoidance at intersections [57] and highways [22, 23], as well as traffic coordination [58].

In [59] a mechanism for using the multiple frequency bands allocated by DSRC is proposed. In this scheme a common channel (to which the stations switch periodically in a synchronized manner) is introduced to coordinate the transmissions of all stations.

The physical layer of IEEE 802.11b uses direct sequence spread spectrum (DSSS) modulations. DSSS has very desirable properties allowing the implementation of code-division multiple access (CDMA) systems, reduced multipath fading, and immunity to narrowband interference. Furthermore, since DSSS is implemented in 802.11b hardware, it allows for relatively convenient and inexpensive testbeds. As a consequence,

many researchers use DSSS (or 802.11b) as the physical layer in their investigations [60–62].

It has been shown in [24, 54, 63] that, with realistic propagation models, the bit error rate (BER) of DSRC can be very high, imposing significant challenges on higher layers. The problem can be traced to the design of 802.11a that was optimized for local area networks with no or low mobility. However, in IVC systems the mobility can be very high, and the equalization techniques designed for low mobility can barely handle the resulting fast fading conditions characterizing IVC systems.

Other disadvantages associated with 802.11 and DSRC IVC systems are due to the initial design of 802.11 that was geared toward local area networks. All features available in infrastructure mode are unavailable in an IVC context (where no access points exist). Furthermore, for ad-hoc mode, the standard assumes that all wireless nodes are in range of each other. While several research papers geared toward ad-hoc networks focused on improving the correctness and performance of 802.11 in multihop scenarios, the schemes have not been standardized and are likely to result in large overheads in IVC systems.

Finally, as we showed earlier, many applications benefit from geographical addressing, which is not supported by 802.11. It is true that 802.11 can be used in broadcast mode (with all recipients pushing the received packet to the network layer) and have the addressing handled by the network layer. However, in this case, several of the features of 802.11 (e.g., reliability) would not be available.

Bluetooth

Bluetooth (standardized at IEEE 802.15.1) [64] is a wireless standard for short-range communication of data meant to eliminate the need for low-data-rate wired connections (it is often referred to as a personal area network, PAN). In the most common configuration, devices form piconets coordinated by a master and with up to seven active slaves in an ad hoc fashion. The standard also allows for overlapping piconets to organize into multihop networks called scatternets.

Bluetooth technology is inexpensive and easy to use. If it is deployed in a vehicle, it could also be used to connect, for example, the stereo with MP3 players or mobile phones. Furthermore, the 1 Mb/s raw bandwidth afforded by the standard is likely to be sufficient for some applications. Some high-end cars already have Bluetooth included in their standard packages (primarily geared toward connecting cellular phones to the vehicle's speaker system). Considering these advantages, several papers propose and evaluate Bluetooth-based IVC systems [35, 65, 66].

However, Bluetooth has several drawbacks in an IVC context. Perhaps the most important drawback is that Bluetooth imposes a piconet structure which is difficult to maintain in IVC systems that are much more dynamic than the stationary systems Bluetooth targets. It was shown, using accurate Bluetooth simulations, that piconet and scatternet formation may take as long as 7 and 45 s, respectively [65]. Furthermore, new nodes joining existing piconets encounter significant delays [67]. Finally, while the specifications allows for transmission ranges of up to 100 m, almost all current chipsets only allow for ranges of up to 10 m (the lowest specified in the standard). Even the 100 m range is considerably smaller than that of DSRC.

Cellular Communication Standards

Cellular networks cover large areas and may be a good solution for VC systems when vehicles are outside major cities and highways. However, cellular systems were not designed and provisioned for simultaneous utilization by a large number of users for long periods of time at high traffic volumes. These inherently single-hop networks rely heavily on centralized infrastructure (base stations) to coordinate the transmissions of mobile nodes.

Research projects in Germany and Italy have evaluated GSM/GPRS and 3G systems [68] for IVC systems [69] The main arguments for using a mobile telephony standard for IVC systems is that the infrastructure is already there, and in the near future most vehicles in Europe will have access to these networks. Furthermore, 3G systems support long-range communications, offer quality of service guarantees, and were designed for high-speed mobility. Finally, the freedom to assign different spreading factors to different stations allows trade-offs between the robustness of transmission and the capacity allocated to each station.

The 3G system used in Europe is the Universal Mobile Telecommunications System (UMTS), with the UMTS terrestrial radio access network (UTRAN). Two implementations for duplex communications are defined: *UTRA-TDD* uses time-division duplex, while *UTRA-FDD* uses frequency-division duplex. In the Fleetnet project [70] an ad hoc mode of UTRA-TDD was proposed for IVC systems [69, 71, 72]. The main challenges in adapting a UTRA-TDD system are ensuring tight time synchronization, power control (essential for CDMA), and a decentralized resource management scheme [69].

The problem of time synchronization can be solved by using the global positioning system (GPS) for coarse time synchronization and using additional synchronization sequences at the beginning of data bursts [69, 71]. The problem of power control can be solved by only allowing one station to transmit in any one slot (with the drawback of unused slots common to all scheduled time-division multiple access [TDMA] systems [69]). This drawback can be mitigated by using a reservation scheme (e.g., R-ALOHA [69]) that uses fixed reservation only for a small number of slots and reserves the rest on demand.

In [71] an analysis of the suitability of the physical layer of 802.11b and UTRA-TDD for IVC systems concluded that while 802.11b works reasonably well in highway scenarios, multipath makes communications in the cities practically impossible. In contrast, UTRA-TDD has no problems in either environment.

For the UTRA-TDD system, three retransmission strategies (stop and wait [SW], goback-n [GBN], and selective repeat [SR]) have been evaluated [72]. The conclusion of the study is that GBN is a good solution, providing performance similar to SR without the extra complexity.

Other Medium Access Schemes

The highly dynamic environment and lack of an obvious central coordination point result in less than optimal efficiency or significant implementation difficulties for many existing MAC protocols. Therefore, many new protocols or modifications of existing ones have been proposed specifically for IVC systems. A survey of MAC protocols for IVC systems is available in [73].

While not particularly efficient, pure ALOHA [50] is extremely simple to implement and may be a good choice for networks with minimal traffic load [74]. Alternatively, R-ALOHA [75] can improve the efficiency of the MAC layer but require (tight) time synchronization, a feature not straightforward to achieve in an IVC system.

To solve the problem of synchronization in a slotted system, [76] proposes a new MAC protocol called VWMN in which each vehicle sends out beacons in order to synchronize slots with its neighbors. In [77] a dedicated frequency with a

Protocol	Range	Data rate	Fully distributed	Slotted	BW and delay guarantees	Standard
DSRC	300 m	10–50 Mb/s	Yes	No	No	Yes
Bluetooth	< 100 m	1 Mb/s	No	Yes	Yes	Yes
3G Cellular	> 1 km	< 1 Mb/s	Custom	Yes	Yes	No
Custom	N/A	N/A	Yes	Most	Most	No

■ Table 2. *Comparison of considered IVC MAC protocols.*

carefully planned train of pulses is used to achieve fine-grained time synchronization.

Some protocols offer new features not available by any of the existing ones; in [75] a reliable broadcast based on R-ALOHA is proposed, and its performance is evaluated; a MAC protocol allowing for multiple channel utilization in DSRC, leading to increased system capacity, is proposed in [78].

Other protocols are designed specifically to support a networking layer with geographical addressing (in effect a cross-layer design) [22, 79].

In an interesting approach, the V-PEACE MAC layer [80] takes advantage of the (assumed) unique locations of each vehicle to assign ownership in a slotted MAC scheme. This idea has also been explored in the context of assigning CDMA codes [81].

While CDMA system have very desirable properties (resilience to frequency-selective multipath fading and narrowband noise, no hard limit on capacity, etc.), in addition to code assignment, power control is critical. While in a centralized scheme (e.g., in cellular communications) power control is relatively easy to achieve (as nodes only have to control their power as received by the base station), in a multihop environment it is practically impossible to achieve power control with respect to all receivers (practically all neighbors of a vehicle).

Orthogonal frequency-division multiplexing (OFDM) is far better suited in this respect, as tight power control is not critical. However, OFDM relies on measurements of the channel characteristics for its success; hence, special attention has to be paid to ensure that transmissions complete before the measurements become obsolete [54].

Numerous papers have proposed new protocols for both the physical and link layers of an IVC system. However, it is important to consider that to enable some very desirable applications (e.g., Internet access), an IVC system will eventually connect to some kind of RVC infrastructure (most likely SRVC at least in the near future). Therefore, we believe that an IVC system should use one of the existing communication standards, ideally with minimal modifications. The development of a new standard may be a significant obstacle (especially if competing proposals are considered) in the development of a new IVC system. Furthermore, many new vehicles are already equipped with network access equipment (e.g., cellular, Bluetooth). Finally, many of the new protocols are focused on a single class of application and are evaluated using less than realistic physical layer models.

Summary

Table 2 presents a comparison of the presented MAC approaches from several perspectives. In terms of range (and reliability), the cellular standards have a clear advantage, as they were specifically designed to cover a large area and cope with high mobility. However, the usual trade-off applies, and data rate is sacrificed at the expense of this increase in range and reliability. Being derived from 802.11 with its associated ad hoc mode, DSRC (and the custom protocols) is off-the-shelf distributed. In contrast, the cellular protocols require extensive customization to ensure that the management usually constrained to the base station is distributed. DSRC is the only protocol of the group that does not rely on a slotted structure. On the upside, this eliminates the need for slot synchronization; however, the lack of clearly defined slots and the resulting random access of the medium makes strict guarantees on bandwidth and delay challenging (if not impossible).

The Network Layer

Traditionally, the network layer is responsible for addressing (naming the elements of the network), routing (finding good paths), and forwarding (actual movement of the packets) data between sources and destinations. In this section we mainly address routing and forwarding.

In an MIVC or HVC system, similar to a MANET, data has to be forwarded in multiple hops from a sender to one or several receivers. A few of the proposed protocols are tested on small testbeds; the vast majority, however, rely on simulations with varying degrees of detail.

An MIVC system has no physical boundaries, (in the extreme, all vehicles on a continent could form an MIVC system). Clearly the capacity of such a large system does not scale; therefore, usually it is assumed that data is only forwarded to vehicles within a specific target *area*.

Address Mapping

The applications presented in Section 4 require either geographical or fixed addressing. In turn, the network layer may provide either geographical or fixed addressing. In case of a mismatch, it also needs to provide a mapping service between them:

- If fixed addresses are used in an IVC system, a query may be flooded in the target area. Any vehicles in the target area will reply with their fixed addresses. Then the message can be unicast to each vehicle (or better yet, multicast). More elaborate and scalable protocols mapping fixed to geographical addresses are proposed in the literature [82, 83].
- If geographical addresses are used, an additional identification field may augment the geographical address (e.g., destination is a vehicle up to 1 mile behind and a vehicle identification number [VIN] equal to xxxxx) such that the message is delivered to only one vehicle.

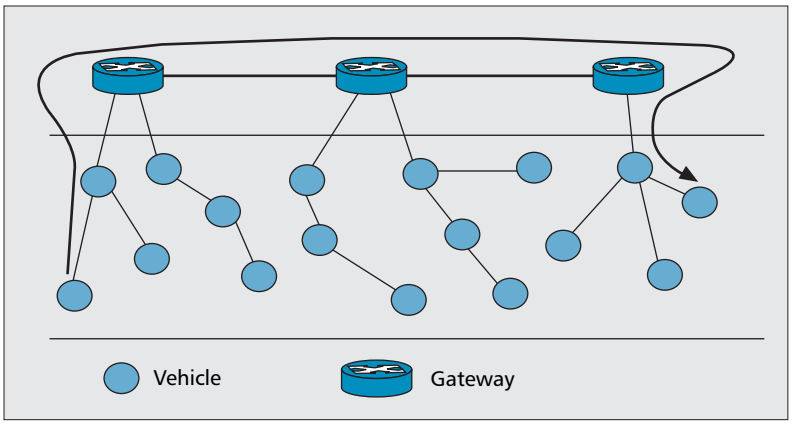


Figure 3. *An HVC system featuring gateways providing "shortcuts" to a distant destination.*

Research on routing protocols for general MANETs has traditionally been focused on unicast routing with fixed addressing [84, 85]. However, different IVC applications require different types of addressing. First, an application may need to use unicast or multicast addressing. Second, either geographical addresses or fixed addresses may be needed. Arguably, geographical addressing is naturally better suited for multicast.

Therefore, the routing protocols that has been proposed for MIVC systems can be classified into three basic groups:

- *Unicast routing with fixed addresses* may be used by comfort applications (e.g., onboard games and file transfers).
- *Unicast routing with geographical addresses* may be used to increase routing efficiency in the same types of applications as unicast with fixed addressing.
- Although theoretically possible, *multicast routing with fixed addresses* would incur huge overhead in maintaining the multicast groups.
- Most envisioned applications in IVC systems will require *multicast routing with geographical addresses* (e.g., emergency warning messages and traffic monitoring applications).

In the following sections we present some of the current state-of-the-art solutions for each group of routing protocols. Although the protocols are introduced as part of the group for which they were originally designed, some of them can also be used in other types of data forwarding. We also present an application layer forwarding mechanism called diffusion, recently proposed in some papers.

Unicast Routing with Fixed Addresses

Two types of routing protocols are commonly proposed for applications that require unicast routing with fixed addresses: AODV-based protocols and cluster-based protocols.

Protocols Based on AODV — On-demand unicast routing protocols such as AODV [14] are designed for general-purpose MANETs and do not maintain routes unless they are needed. Hence, they have reduced overhead, especially in scenarios with a small number of network flows.

AODV is a reactive protocol in which a node performs a route discovery process before a packet is sent to the intended destination. In short, the source node initiates the route discovery process by flooding a route request (RREQ) message for the intended destination across the network. Nodes receiving the RREQ update their routing tables with information about the source node and then rebroadcast the RREQ. When the destination node receives the RREQ, it unicasts a route reply (RREP) back to the source. The RREP is forwarded back to the source node on the reverse path of the RREQ that has been stored at intermediate nodes. When the source node receives the RREP, a path to the destination has been set up, and it can begin the data transfer. As long as the route is active, it can be used. If a link breaks while the route is active, a route error (RERR) is propagated back to the source node, which can restart the route discovery process if needed.

Since AODV has become a standard for ad-hoc networks [86], it has also been proposed for IVC systems [87, 88]. However, since an IVC system has no natural boundaries, AODV needs to be modified before it can be used in IVC systems. In [89] AODV is modified such that RREQs are only forwarded within the ZOR.

However, in [90] it is shown in real-world experiments with six vehicles that AODV is unsuitable for multihop communication in an IVC system. The route discovery mechanism was not able to set up reliable routes in the rapidly changing vehicular network. Another problem with AODV is that it was developed for small networks. For larger networks, the route discovery phase may cause network congestion and become unreliable due to broken links.

In [91] another solution is therefore proposed. An HVC system is assumed, as shown in Fig. 3, in which all vehicles are associated with gateways placed along the roads. A vehicle can reach its gateway within a predefined maximum number of hops. The gateway provides access to the Internet and also acts as a relay station to vehicles associated with other gateways. The route discovery phase in AODV is modified so that the RREQ is only flooded up to the maximum number of hops. If the intended destination is not associated with the same gateway as the source, the gateway will forward the RREQ to the other gateways.

The gateways will then act as intermediate nodes between the source and the destination. As a vehicle moves, controlled handovers are performed between gateways, similar to cellular networks.

Cluster-Based Routing Protocols — Cluster-based routing [92] has been considered suitable for VANETs since vehicles driving on a highway may naturally form clusters. In a cluster-based IVC system [93–95] vehicles form virtual clusters coordinated by cluster heads, (e.g., Fig. 4). Vehicles in a cluster communicate via direct links. Intercluster communication is performed via the cluster heads.

In [94] a node can have one of the following three roles: cluster head, gateway, or member. Each cluster has exactly one cluster head. If a node is connected to more than one cluster, it is called a gateway. All other nodes in the cluster are members. The cluster head maintains information about its members and gateways. Packets are forwarded from source to destination by a procedure similar to AODV. The main difference is that only cluster heads and gateways forward packets (both data and control).

A significant hurdle for these protocols, similar to the case of Bluetooth at the data link layer, is the delay and overhead involved in forming and maintaining these clusters in fast-changing IVC systems. Therefore, some of these routing protocols rely on roadside base stations for the formation and maintenance of clusters.

Unicast Routing with Geographical Addresses

Most papers focusing on unicast routing with geographical addresses propose modified versions of the Greedy Perimeter

Stateless Routing (GPSR) protocol [96]. Some papers propose to enhance the routing mechanism by including the underlying road map information, and only routing data packets along streets and intersections.

GPSR is a location-based unicast protocol in which a node only maintains information about its neighbors (i.e., no route information is needed). Therefore, it is less prone to the path disruption problems of AODV. In GPSR it is assumed that a source node knows the location of the intended destination. Also, each node has current information about the position of its neighbors (obtained via a beaconing procedure). All packets include the location of the intended destination. Thus, when a node receives a packet, it can make a locally optimal decision about to which node the packet should be forwarded. The protocol uses two distinct methods for forwarding packets: greedy forwarding and perimeter forwarding. In greedy forwarding the packet is forwarded to the node's neighbor that is geographically closest to the intended destination. However, if no such node exists (due to a gap region with no nodes between the current node and the destination), perimeter forwarding is used instead. In perimeter forwarding the packet is forwarded around the perimeter of this gap region to the counterclockwise neighbor of the current node. Greedy forwarding is resumed as soon as the gap region is bypassed.

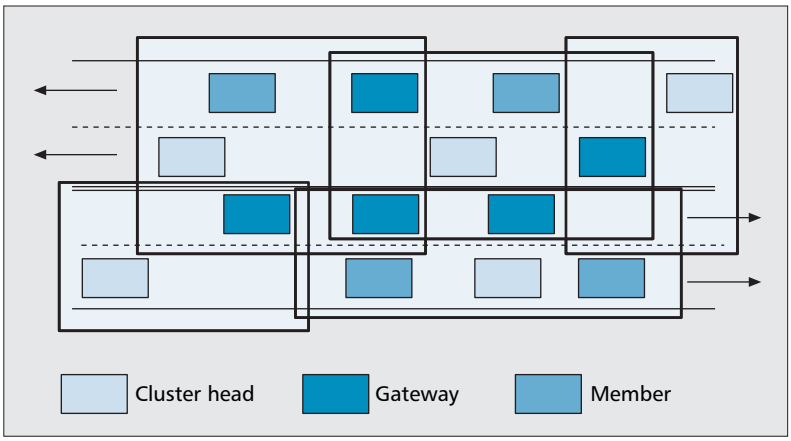


Figure 4. *Vehicles organized in clusters featuring cluster heads, gateways, and members.*

Due to the stateless nature of GPSR, modified versions of the protocol have been proposed for IVC systems [97, 98]. The basic idea of these papers is that the protocol uses the digital map in the navigation system to calculate a preferred route from source to destination. The route consists of a number of hops via specific intermediate hops (similar to loose source routing in the Internet). In [97] an HVC system is assumed, and each intermediate hop corresponds to a roadside hotspot. In [83] each intermediate hop corresponds to a road intersection. The preferred route is included in the packet; then the packet is forwarded from source to destination using GPSR via each intermediate hop.

In [99] a digital map is used to enhance the protocol performance (especially in city scenarios). The paper describes an experiment with two and three cars both in a city environment and on a highway. The experiments showed that the radio range for IEEE 802.11 was much smaller in the city than on the highway due to interference from buildings. The radio range may be considerably better in the direction of the street, toward intersections or hotspots, than in other directions.

Multicast Routing with Geographical Addresses

Papers that use multicasting usually assume a geocasting protocol that uses geographical addressing [100]. The objective of a geocast protocol is to forward a message from a source node to nodes within a specified target geographical region. The target geographical region is often called the zone of relevance (ZOR) [101], and is usually specified as a rectangular or circular zone rather than a single coordinate. Additional attributes may be used to further select a subset of target vehicles, such as the direction of movement or type of vehicle.

In those cases where not all vehicles in the ZOR should get the message, the network layer makes a decision if a received packet is to be forwarded to the application or not. However, it is usually assumed that all vehicles within a certain forwarding zone should take part in the routing process.

Most geocast protocols are based on some form of flooding [22, 102–105]. Some papers propose pure flooding of packets [23, 82, 106, 107]. Packets are flooded within a forwarding zone that includes the ZOR. Some geocast protocols that do not rely on flooding have also been proposed, more details can be found in [100].

Many IVC applications need a large ZOR, with a radius of a kilometer or more, and several hundred vehicles may be intended destinations for a packet in rush hour traffic. Therefore, the choice of an intelligent forwarding mechanism is especially important for IVC systems. The performance problems that may occur in a flooding mechanism can be avoided by using an optimized procedure that forwards messages to vehicles within the relevant area while avoiding full flooding. The main problem here is ensuring that all intended destinations receive the message while lowering the overhead.

In [22] a scheme to reduce the number of rebroadcasts (and thus reduce congestion) is proposed. In this scheme, when a node receives a packet and determines that it should forward it, it first determines a waiting time, WT. This waiting time depends on the distance between this node and the previous sender node. The objective of this waiting time is to let nodes further away from the previous sender forward the packet with a higher priority than nodes close to the sender. Note that this is a wireless environment and many (but possibly not all) nodes within range will receive the broadcast transmission. In this way a broadcast storm (packet collisions due to simultaneous forwarding) is avoided, and, in addition, the forwarding is optimized (the number of broadcasting nodes is minimized).

In [22] the waiting time is determined as:

$$WT = WT_{max} - \frac{WT_{max}}{R} \cdot \min\{d, R\}, \tag{1}$$

where R is the maximum transmission range, WT_{max} is the maximum waiting time, and d is the distance to the previous sender node. This algorithm is rather simple and can be improved, although with an increase in complexity. Variants of the algorithm above have been proposed in [102, 105, 108].

Diffusion Mechanisms

Several proposed traffic monitoring applications employ a unique dissemination procedure, sometimes called a *diffusion mechanism* [26, 27, 109].

Diffusion works at the application layer (and is only suitable for some applications) , thus not being a "true" routing mechanism. However, since it considers multihop forwarding of data, it is described here for completeness. In a diffusion

Protocol	Addressing	Uni/Multicast	Path state	Neighbor state	Hierarchical	Easy IP integration
AODV	Fixed	Unicast	Yes	Yes	No	Yes
Cluster	Fixed	Unicast	Yes	Yes	Yes	Yes
GPSR	Geographical	Unicast	No	Yes	No	Yes
Geocasting	Geographical	Multicast	No	No	No	No

■ Table 3. *Comparison of the presented routing approaches for IVC systems.*

mechanism the application collects data from other neighboring vehicles, and aggregates and stores the data (e.g., by maintaining a table of current speeds for different road segments). At regular intervals the current table is broadcast to all neighbors that in turn update their tables, and so on. The result is that the data is "diffused" in the network, each vehicles having more accurate information on the state of nearby traffic (and relatively outdated information from distant regions).

The main advantage of the scheme is its simplicity and good fit for the needs of traffic monitoring applications. The main drawback of the scheme is its limited applicability as a general routing scheme. In [110] a comparison between a geocasting protocol and a diffusion mechanism in a highway scenario is presented. The assumption in [110] is that the relevance of information about a particular phenomenon decreases with the distance to that phenomenon. The authors showed that a diffusion mechanism can achieve good results at a much lower network load.

Recently, a self-organizing traffic information system (SOTIS) for traffic management applications has been proposed [27]. SOTIS uses a diffusion mechanism in which the application in each vehicle aggregates received data and sends out updated information at periodic time intervals. In order to demonstrate its features and feasibility, the authors implemented a prototype. They evaluated the prototype in both simulations and with experiments using four stationary vehicles located close to each other such that total connectivity was obtained. The prototype used IEEE 802.11b in broadcast mode. The simulations showed that SOTIS works well even for very low penetration rates (1–3 percent). The results from the experiments were in accordance with the simulations.

Experiments

Some experiments focused on evaluating multihop routing protocols for vehicular networks. Most experiments used existing unicast routing protocols and involved a limited number of vehicles.

In [111] experiments were conducted with four nodes: a stationary sender, a mobile receiver, and two stationary relays. All nodes used 802.11b, and the routing protocol was OLSR. The experiments were conducted on a loop with the vehicle moving at a speed of 15 mph (24 km/h). The results showed that the throughput varied considerably depending on the location of the vehicles. When the route had to be reestablished, the throughput dropped to zero for several seconds.

In [112] results from experiments with both static and mobile vehicles are presented. The prototype was built using 802.11b and also GPSR with three-hop routing. The location service was implemented using flooding. An extra protocol layer was implemented between the MAC and network layers in order to manage the geographical information needed for GPSR. In the mobile three-hop scenario, four vehicles moved in a loop at city speeds. Throughputs of about 150 kb/s were obtained; however, large variations in the throughput due to rerouting are also present. The experiments showed the importance of only selecting the strongest links for multihop communication. To this end, a suppression mechanism that dropped all received packets from senders farther away than a predefined distance was implemented.

In [90] an experiment with a unicast flooding mechanism is presented. The experiment involved six vehicles moving like a chain. IEEE 802.11b hardware was used for broadcasts, and a flooding mechanism was implemented in the application layer. The flooding mechanism used a selective forwarding procedure with implicit acknowledgments. The results showed that a throughput of about 55 kbytes/s can be obtained with four-hop routes. Since the routing scheme does not rely on explicit routes, no drops in the throughput were reported.

One limitation of most testbeds is that they are based on IEEE 802.11b hardware. While very convenient, this setup limits the control of the lower layers of the networking stack (at best, only allowing changes to the parameters of the 802.11 protocol). Furthermore, 802.11b uses DSSS modulation, while the new DSRC standard (as well as 802.11a and 802.11g) uses OFDM modulation. A testbed based on wireless motes (e.g., Mica2 [113]) would allow changes in the MAC layer, but not in the physical layer. However, we believe that a software radio (e.g., the Gnu radio [114]) would provide the ultimate testbed platform, allowing for changes in practically the entire protocol stack (modulation, channel coding, equalization, etc.).

Summary

Studies have shown that the average lifetime of a link between two vehicles is in the range of a few seconds to a few tens of seconds, even for vehicles traveling in the same direction [115]. A routing protocol for MIVC systems will need to be able to handle these conditions.

Due to the highly dynamic nature of VC systems, mapping fixed addresses into geographical ones has several drawbacks. First, it is expensive in terms of bandwidth, as a query will have to be repeated frequently in order to ensure that the mapping is accurate. Second, it adds unacceptable delay (relevant to applications with real-time requirements). Third, it is unreliable. If the flooding of the query relies on broadcast, it is possible that many vehicles in the target area will not receive the query. It was shown in [24] that DSRC delivers about 50 percent of the packets in a one-hop application. Finally, it requires setting up routing tables bound to become obsolete very soon after their setup.

In fact, it was shown [15] that the last issue alone renders existing MANET protocols inoperable. The authors of [15] used realistic vehicle traces (using real recorded data in combination with CORSIM, a very detailed vehicle simulator) and ns-2 to show that most routes, even between vehicles traveling in the same direction, are short-lived (less than 1 min), and in many cases a route is obsolete as soon as it is established. These results were obtained considering a high penetration rate (20 percent), no errors, and without considering the

Paper	No. of nodes	MAC	Traffic type	Speed	Distance	Throughput
[118]	4	802.11b	TCP	40 km/h	N/A	~800 kb/s
[56]	3	802.11b	UDP	8–113 km/h	< 145 m	500–2300 kb/s
[119]	3	802.11g	UDP	< 5 km/h	N/A	1–5 Mb/s

■ Table 4. *Throughput experiments in IVC systems.*

query phase necessary for mapping fixed addresses into geographical addresses.

Table 3 presents a comparison of the routing approaches presented above (we did not include diffusion as it is not suitable as a general-purpose routing protocol). Both AODV as well as cluster-based routing (which uses AODV for intercluster communications) rely on maintaining multipath routes, a distinct disadvantage in highly mobile MIVC systems. Depending on how it is actually implemented, geocasting may work without maintaining knowledge about its neighbors (the more updated knowledge available, the smaller the flooding overhead but the higher the control overhead [116]). The cluster-based routing protocol pays the penalty of maintaining a (local) hierarchy. Finally, due to its geographical addressing scheme, geocasting may be difficult to integrate with existing IP-based networks (e.g., the Internet) in a hybrid network scenario.

Transport and Security Layers

In this section we will discuss the current state of research regarding the transport layer (including end-to-end quality of service [QoS] issues) and security for IVC systems.

Transport Layer

The transport layer is typically responsible for providing end-to-end services (e.g., reliability and flow control) and sometimes other services (e.g., congestion control). In comparison with the other layers, relatively few papers focus on the transport layer.

End-to-end QoS is crucial for many IVC applications. Without end-to-end guarantees of QoS, many of the potential "killer" applications, (e.g., public safety applications) will not be feasible. For other applications, end-to-end delivery guarantees will be of paramount importance (e.g., toll payments).

For example, in collision warning applications it was shown that in the absence of a congestion control mechanism, vital information may encounter unacceptable delays [23]. Many other applications may need congestion control mechanisms to avoid network overload and long delays [27].

It is a well-known fact that in MANETs, TCP suffers from severe inefficiency and unfairness [117]. Only a few papers have evaluated the existing transport protocols for Internet (TCP and UDP) in IVC systems. In [118] results from an experiment with four cars are presented. The authors achieved a throughput of about 800 kb/s and with large deviations when the cars moved at 40 km/h. In [56] the authors used three cars with a controlled distance between them. They received an average throughput between 500 kb/s (at high speeds and distances) and 2300 kb/s (in a static environment) In [119] a much higher throughput (1–5 Mb/s) was achieved in a video streaming application using 802.11g hardware. In this article the vehicle was almost stationary and communicated with fixed base stations.

From the results summarized in Table 4, it is clear that the current TCP and UDP will suffer at high speeds and long distances. Therefore, IVC systems could benefit from new transport protocols or, at the very least, significant modifications of the standard TCP. In [120] the authors investigate the path characteristics that are relevant for a transport protocol for MIVC systems. Also, a design for a Vehicular Transport Protocol (VTP) is presented. The protocol probes the network and uses statistical data to improve the performance when a connection is disrupted. In [121] the Mobile Control Transport Protocol (MCTP) is proposed based on similar principles as Ad Hoc TCP [122]. An HVC is assumed, and the objective of MCTP is to provide end-to-end QoS between a vehicle and an Internet host via an roadside gateway. Also, a location-aware stateless (similar to HTTP) transport protocol for MIVC systems has recently been proposed [123].

To date, all proposed transport protocols for IVC systems are designed for applications that require unicast routing. Since many envisioned IVC applications require geocasting (i.e., multicast), there is a clear need for new approaches that are not based on traditional transport protocols. The design of a reliable transport protocol for geocasting will clearly be challenging, since geocasting protocols are usually stateless. Thus, we expect that in the near future we will see significant activity in this area.

Security and Privacy

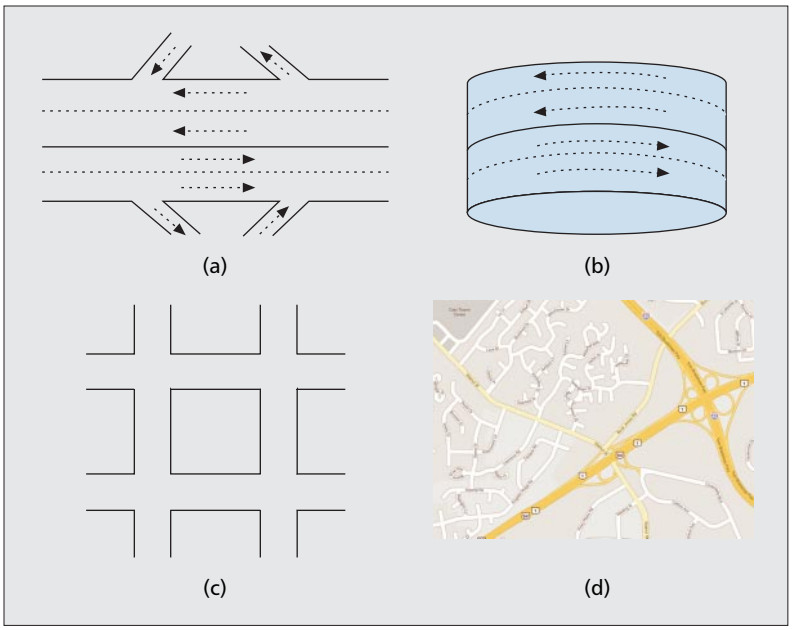
If and when IVC systems become pervasive, they will probably be the largest open access ad hoc networks in existence. The right balance between security and privacy of this network will be of utmost importance for its long-term success. So far, general security issues have not been solved. Most papers on security present solutions for very specific problems. In [28] it is suggested that all vehicles have electronic license plates that have the same functions as ordinary license plates while offering several advantages (e.g., chase assistance from parked cars in tracking a fugitive vehicle). Reference [124] investigates how forged position information can affect both the performance and security of IVC systems.

A couple of recent papers propose more general security architectures. In [125] several security services in IVC systems are discussed, and a security architecture is proposed. In [126] an integrated communication and security architecture called Communications Architecture for Reliable Adaptive Vehicular Ad Hoc Networks (CARAVAN) is presented. The objective is to develop communication protocols for IVC systems that mitigate the threat of various security attacks.

Many other questions related to security and privacy are outside the scope of technical system design, such as whether police officers should be able to fine a driver on a speed violation that happened a week ago (recorded by the vehicle and reported upon request), a parent should be able to localize the vehicle of a child, or a police officer should be able to stop a vehicle remotely.

Performance Modeling Issues

Due to the cost and difficulties involved in deploying large vehicular testbeds, the majority of proposed IVC systems have



■ **Figure 5.** *Road models: a) straight road (highway); b) circular road; c) road grid; d) real(istic) road.*

been evaluated via simulations. The results obtained from theoretical investigations or simulations are highly dependent on the models used. Numerous performance models exist for general MANETs. However, the behavior of nodes and channels in an IVC system is very different from the general MANET system. Therefore, the models used to evaluate IVC systems can and should be rather different than those for MANETs. In this section we present and discuss some of the related issues.

Mobility Models

Any simulation of a MANET has to employ some mobility model. It is well known that mobility models can significantly affect simulation results (quantitatively as well as qualitatively) [13]. For MANETs, the random waypoint model (RWP) is by far the most popular mobility model [127].

In a vehicular network nodes (vehicles) can only move along streets, prompting the need for a *road model*. Another important aspect in a vehicular network is that nodes do not move independent of each other; they move according to fairly well established *traffic models*. In the literature four types of road models are often considered: the straight highway, the circular highway, the road grid, and real road maps.

The straight highway (shown in Fig. 5a) is a reasonable model for highways outside cities. In this model vehicles move in lanes, in either one or two directions. The main characteristic of a straight highway model is that messages transmitted between vehicles only move along one dimension. The straight highway is simple to implement and is therefore the most used road model in the literature [22, 23, 26, 27, 61, 71, 78, 102, 106, 109]. A variation of the straight highway is the circular road model, depicted in Fig. 5b. In this model vehicles also move in one or several lanes similar to the straight highway. However, in this case the road is a closed loop, where no vehicles can enter or leave the road [63, 94, 115].

The road grid (Fig. 5c) is fairly representative for urban roads and town centers, where the straight highway model is not applicable. In this model traffic moves in two or even three dimensions. The road grid is more complicated to implement than the straight highway and is therefore mostly used in very specific scenarios [24, 65, 71, 82]. As an alternative to a road grid model, a real road map (e.g., Fig. 5d) is used in some papers [15, 29, 83, 93, 128].

Traffic modeling is a well-known research area in civil engineering. It is important to model vehicular traffic during the design phase of new roads and intersections. There are a number of traffic models that accurately mimic vehicle traffic, and a good survey focused on IVC systems can be found in [129].

The importance of using correct mobility models for IVC systems has been shown in [130]. In this article the performance of an RWP model for MANETs is compared to a grid model for vehicular traffic. The simulations show that the system performs worse when the grid model is used, thereby showing that the results for general MANETs may not be applicable to vehicular networks.

Simulation Models

Usually, the simulation of an IVC system includes two stages. In the first stage the vehicle movements are determined, usually using a *traffic simulator* [17, 18]. The input of the traffic simulator includes the road model, scenario parameters (maximum speed, rates of vehicle arrivals and departures, etc.). The output is a trace file where every vehicle's location is determined at every time instant for the entire simulation time. In the second stage the trace file is used as input in a network simulator [131, 132]. Each vehicle becomes a node in an ad hoc network with the trace file specifying the movements of each node.

One important aspect in a simulation model for an IVC system is the driver's response to the IVC application. The reaction of the drivers in different situations will affect, for example, traffic throughput. For example, a driver who receives a collision warning message may either hit the breaks or reroute depending on the distance to the accident scene. If all vehicles within a certain ZOR do the same, this will probably cause traffic problems somewhere else.

However, to our knowledge, there are no papers that have actually combined the traffic and network models in evaluations. This is mostly due to the fact that the traffic and network models are implemented in two separated simulation tools.

Therefore, there is a clear need for integrated traffic and network simulators to evaluate of the performance of IVC systems. A first cut at building an integrated simulator is presented in [133] where the authors integrated STRAW, a street mobility module, with SWANS [134], a Java-based network simulator. However, significantly more work is needed for this simulator to gain wide acceptance in the community. Also, in [135] an integrated traffic and network simulator is used to investigate adaptive cruise control. However, this simulator assumes an SIVC system, and only the physical and MAC layers are implemented.

Communication Channel Models

Accurate models for the communication channel are a prerequisite for meaningful simulation results. Most simulation models for IVC systems use the classical free space propagation model without fading. Packets are received correctly if the receiving node is within a predefined distance from the sender. The model does not consider speed, fading or interference from buildings. In [63] a classical two-ray ground

model is compared with a more realistic Nakagami propagation model. Large differences in the reception probability of 802.11 broadcast packets could be seen. Therefore, there is a clear need for more accurate channel models for IVC systems.

IVC systems are, at the physical layer, in many aspects similar to a cellular system. There has been considerable work in modeling communication channels for cellular systems. However, in IVC systems the communication range is significantly smaller, and both the transmitter and receiver are mobile, thus prompting the need for new channel models. In [24] the physical layer of DSRC was modeled in detail and used in the simulations. The results showed high BERs due to the high velocity of the vehicles.

In a number of papers the physical channel behavior for IVC systems has been measured. Many papers used prototypes based on IEEE 802.11b (2.4GHz ISM band) [34, 55, 56, 99, 111, 118]. One paper that evaluates a prototype based on IEEE 802.11a (5.8GHz ISM band) is [57]. The channel behavior for a 60 GHz millimeter wave system is evaluated in [136]. The results of the experiments differ significantly from the free space propagation commonly used in network simulators. Furthermore, the results depend not only on the hardware used, but also on the scenario (e.g., urban grid vs. highway) [99].

Measurement results are difficult to use directly in simulations. Therefore, a number of papers have performed detailed simulations or theoretical analysis (e.g., based on ray tracing) of the physical channel in an IVC system [38, 54, 60, 137, 138]. Also, in [139] it is shown that channel coding can improve the BERs in the very challenging communication channels in IVC systems.

Unfortunately, none of those often very accurate models are commonly used in simulations of the higher layers. The challenge is therefore to use the obtained results and incorporate them in the networking simulators. Only with correct channel models can the simulations be assumed to accurately mimic the behavior of a real IVC system.

Related Projects

A number of research projects around the world have been focusing on inter-vehicle communication systems. In this section we present some of the larger projects.

Early Projects

In Europe projects such as DRIVE [140] investigated IVC systems for a safer and environmentally friendly transportation. The Program for European Traffic with Highest Efficiency and Unprecedented Safety (PROMETHEUS) [141] was launched in 1986 by the European Automotive Industry; its main objective was to make driving in Europe safer, more economical, more environmentally acceptable, more comfortable, and more efficient.

PATH

The PATH project [142] is a collaboration between the California Department of Transportation (Caltrans), the University of California, other public and private academic institutions, and industry. Its main mission is to apply advanced technology to increase highway capacity and safety, and reduce traffic congestion, air pollution, and energy consumption.

PATH has generated a number of publications and prototypes in the area of IVC systems primarily focused on cooperative driving and vehicle platooning [12, 30, 31]. As part of the project they developed SHIFT, a fairly realistic traffic simulator that also integrates communication components, thus being especially suitable for the evaluation of IVC systems [18]. As part of the PATH project, a successful experiment with eight vehicles in a platoon formation [30] was demonstrated.

Fleetnet

Fleetnet — Internet on the Road [70] was a project that was set up by a German consortium of six companies and three universities (Daimler-Chrysler AG, Fraunhofer Institut für offene Kommunikationssysteme [FOKUS], NEC Europe Ltd., Robert Bosch GmbH, Siemens AG, TEMIC Speech Dialog Systems GmbH, Universities of Hannover and Mannheim, and Technische Universität Hamburg-Harburg and Braunschweig). The project was funded between 2000 and 2003.

The main objective of the Fleetnet project was to develop a platform for IVC systems. The project focused on three classes of applications: cooperative driving, traffic information, and comfort applications (e.g., games and Internet access). Fleetnet researchers have published numerous papers [27, 59, 69, 71, 72, 128]; most of them propose solutions based on the UMTS-UTRA at the data link layer (although they switched to 802.11 for the latter part of the project).

Since 2004 (and until 2008), most of the members of the Fleetnet consortium are working on a new project named Network on Wheels [143]. The main objectives of this project are to solve questions on the communication protocols and data security for targeted vehicular communications. They also plan a functional testbed.

CarTalk 2000

CarTalk 2000 [144] (2001–2004) was funded by the European Union within the 5th Framework program. The partners in the project were Daimler-Chrysler AG, Centro Ricerche Fiat, Robert Bosch GmbH, Siemens, the Netherlands Organization for Applied Scientific Research, the University of Cologne, and the University of Stuttgart. An overview of the project can be found in [145].

The main objectives of the project were the development of cooperative driver assistance systems and a self-organizing ad hoc radio network as the basis for communication with the aim of preparing a future standard.

CarTalk 2000 has generated several research publications, such as [146, 147], with several papers focused on geocasting algorithms for vehicular environments [104, 128].

Activities in Japan and Italy

The Japan Automobile Research Institute (JARI), formerly the Association of Electronic Technology for Automobile Traffic and Driving (JSK), has in a number of projects studied IVC systems since the early 1980s. In the 1990s the project focused on cooperative driving; now it has shifted toward the standardization of IVC systems [6, 148]. One of the projects demonstrated a prototype for traffic coordination (DEMO 2000) [58, 149].

In Italy the Telecommunication Network for Cooperative Driving (TELCO) project has investigated the feasibility of an IVC system working at millimeter waves (between 60 and 64 GHz) [21]. They have also investigated IVC systems based on GPRS and 3G networks [9, 150].

Recent Projects

The NSF-sponsored zero infrastructure projects [151] are studying the effects of system penetration on traffic monitor-

ing and safety applications.

The E-road project [26] focuses on collaborative computing aspects required for traffic monitoring in an IVC system. The Drive-thru-Internet [152, 153] project is experimenting with 802.11-based SRVC systems.

In Europe there are several ongoing projects that includes IVC systems. SAFESPOT [154] is an integrated research project co-funded by the European Commission Information Society Technologies (IST) among the initiatives of the 6th Framework Program. The objective of the project is to understand how intelligent vehicles and intelligent roads can cooperate to increase road safety.

PReVENT [155] is another integrated project within the European Union. One of the objectives of this project is to contribute to the congregation and cooperation of European and national organizations and their road transport safety initiatives. One of its subprojects is WILLWARN, which is developing a communication-based system that extends the driver's horizon and intelligently warns the driver of dangerous situations ahead.

COMeSafety [156] is a recently started project that is focused on all issues related to vehicle-to-vehicle and vehicle-to-infrastructure communications as the basis for cooperative intelligent road transport systems.

The Car2Car Communication Consortium [157], a nonprofit organization initiated by the European vehicle manufacturers, is open to suppliers, research organizations, and other partners. Its main objective is to increase road traffic safety and efficiency by means of inter-vehicle communication.

Several of these projects demonstrate vehicle-to-vehicle and roadside-to-vehicle communication on small testbeds (commonly implemented using 802.11-based hardware).

Conclusion

In conclusion, IVC systems can enable several classes of applications that can make road travel safer (by avoiding many types of collisions), more efficient (by decreasing travel time, avoiding traffic congestion, and increasing road capacity), as well as more pleasant (through locally updated information). The appealing characteristic of IVC systems is their lack of reliance on roadside infrastructure, commonly thought to be too expensive to be ubiquitously deployed in the near future.

However, similar to the case of MANETs, the lack of infrastructure and its role as a central coordination point leads to specific networking problems, prompting the need for fully distributed protocols. IVC systems introduce additional challenges for network protocol designers. In particular, the mobility of vehicles results in a considerable rate of link changes (and a corresponding very short lifetime for multihop paths). This renders protocols that rely on knowledge of the state of the system (even if only local) inefficient due to the need for frequent updates. In addition, many of the applications of IVC systems need a radically different addressing mode than typical MANET applications, and hence require (or may benefit from) a different networking stack.

Fueled by the need for new solutions, many networking protocols for IVC systems have been proposed in the literature. One common drawback of these protocols is that they cater to the needs of one specific application while ignoring others. Ideally, similar to the case of the Internet, the network should provide a set of services that can be used by all (including yet to be invented) network applications. A second common drawback of the proposed protocols is that they are evaluated in less than ideal situations. In particular, in testbed evaluations (due to logistical difficulties and cost) typically only a few vehicles with limited mobility are used. When simulations are used for evaluation, most traffic network simulator combos have poor physical radio propagation models (and many of them also have poor vehicular traffic models). Finally, almost all protocols evaluate network-level performance (message delays, packet delivery ratio, efficiency, etc.) instead of evaluating the impact of the IVC system on the performance of the vehicular system (reduction in the number of collisions, travel time, congestion, etc.).

At the network access layer, the research community seems to converge toward a short-range local communication paradigm, with physical and medium access technologies borrowed from the wireless local area network standards. However, at the network layer, a wide range of protocols are being proposed by many researchers, while others show that many of these protocols are doomed to fail using more realistic models. None of the currently proposed routing protocols have been designed to cover a large range of applications. At the transport layer the situation is even worse, with very few researchers even considering problems at this layer (perhaps understandably considering the lack of consensus at the network layer).

Thus, despite considerable preliminary work in the area, there is a large scope for research on *comprehensive* networking and transport layer solutions that can address the needs of many classes of applications. Due to the difficulty of testbed evaluation, there is also a need for realistic evaluation tools in this area (possibly something similar to what ns-2 brought to the traditional networking world, ideally without the suite of problems that plague ns-2).

Thus, IVC systems have significant potential as well as challenges. Many existing approaches provide valuable leads in solving individual pieces of the puzzle, but a considerable amount of work is still needed in piecing together and evaluating the performance of the entire system.

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