State of the art and research challenges for VANETs

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***Abstract*—Recent advances in wireless communications technology and car industry made it possible to consider wireless Ad-hoc (or mixed Ad-hoc/infrastructure) networks, providing connectivity among vehicles on the road. Such network, often referred to as VANET (Vehicular Ad-hoc Network) is seen to be one of the most valuable concept for improving efficiency and safety of the future transportations, as well as boosting operators' revenue. Thus, several ongoing research projects supported by industry, governments and academia, establishing standards for VANET networks. This paper covers current research challenges and future applications for such networks, discusses possible deployment scenarios and provides some insights to the state-of-the-art of the current standardization of interfaces and protocols on a global scale.**

I. Introduction

Vehicular connectivity can be fairly considered a future killer application, adding extra value to the car industry and operator's services. Taking into account the constant growth of automotive market and the increasing demand for the car safety, also driven by regulatory (governmental) domain, the potential of car-to-car connectivity is immense. Such system should be suitable for a wide spectrum of applications, including safety-related, traffic and fleet control, and entertainment. First, some issues concerning architecture, security, routing, performance or QoS need to be investigated. Standardization of interfaces and protocols should be carefully planned to ensure interoperability, as vehicles coming from different vendors must communicate smoothly. Having different competing systems would result in decreased market penetration and poor overall system efficiency, thus only one common system can be deployed. And finally, wise deployment strategy has to be proposed, as most application would become functional only after certain market penetration is reached.

The first milestone of standardization process was the allocation of 75 MHz of DSRC (Dedicated Short Range Communications) spectrum to accommodate Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication for safety-related applications by US Federal Communications Commission (1999). Commercial applications are also allowed to operate in this spectrum, as long as they do not interfere with its primary purpose. Next step is devising of a deployment model for DSRC to support both safety and non-safety applications over an VII (Vehicle Infrastructure Integration) Network, whereas the research community is looking at the design and usage of vehicular communication.

The rest of this article is organized as follows: the next section briefly mentions potential applications of car-to-car networking. Then the current research challenges and their possible solutions are discussed. Section 4 introduces market penetration and deployment strategy issues. Further we present the current standardization process, focusing on European, US and Japanese activities. Our concluding remarks are presented in the last section.

II. VANET applications

Integrating a network interface, GPS receiver, different sensors and on-board computer gives an opportunity to build a powerful car-safety system, capable of gathering, processing and distributing information. Numerous applications can be deployed in a network established with such equipped vehicles and proper infrastructure. Generally, from the connectivity point of view they could be divided into four main groups: car-to-car traffic, car-to-infrastructure, car-to-home and routing based applications. These applications are either safety-related or comfort-related (commercial).

A. Safety-related applications

Safety-related applications may be grouped in three main classes: assistance (navigation, cooperative collision avoidance, and lane-changing), information (speed limit or work zone info) and warning (post crash, obstacle or road condition warnings). They usually demand direct communication due to their delay-critical nature. One such application would be emergency notifications, e.g. emergency braking alarms. In case of an accident (the airbag trigger event) or sudden hard breaking, a notification is sent to the following cars. That information could also be propagated by cars driving in the opposite direction and, thereby, conveyed to the vehicles that might run into the accident.

Another, more advanced example is cooperative driver assistance system, which exploits the exchange of sensor data or other status information among cars. The basic idea is to broaden the range of perception of the driver beyond his field of vision and further on to assist the driver with autonomous assistance applications. By transmitting this data to cars following on the same road, the drivers get information about hazards, obstacles or traffic flow ahead, resulting in more efficient and safe driving. Some applications of this kind are only applicable if the penetration of VANET enabled cars is high enough.

B. Comfort (commercial) applications

The general aim of these applications is to improve passenger comfort and traffic efficiency. That could include nearest POI (Points Of Interest) localization, current traffic or weather

1-4244-1457-1/08/$25.00 © IEEE
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information and interactive communication. All kinds of applications, which may run on top of TCP/IP stack might be applied here, e.g. online games or instant messaging. Another application is reception of data from commercial vehicles and roadside infrastructure about their businesses ('wireless advertising'). Enterprises (shopping malls, fast foods, gas stations, hotels) can set up stationary gateways to transmit marketing data to potential customers passing by. Furthermore, these services could be integrated with electronic payments.

The important feature of comfort/commercial applications is that they should not interfere with safety applications. In this context traffic prioritizing and use of separate physical channels is a viable solution.

III. Research Challenges in VANETs

When deploying of a vehicular networking system, several issues have to be resolved, often from distant fields of expertise, ranging from applications development up to economical issues. VANET could be considered as an instantiation of MANET network; however their behavior is fundamentally different. These unique characteristics of these networks are as follows:

- rapid topology changes and frequent fragmentation, resulting in small effective network diameter
- virtually no power constrains
- variable, highly dynamic scale and network density
- driver might adjust his behavior reacting to the data received from the network, inflicting a topology change

Here we briefly mention some of the core research challenges that need to be addressed.

A. Wireless Access technology

There are several wireless access standards that could be used as a base for VANET connectivity. In general the aim is to provide a set of air interface protocols and parameters for high-speed vehicular communication using one or more of several available media. Some of the core technologies include:

1) Cellular technology (2/2.5/3G): The main advantages of 2/2.5G technology are coverage and reliable security, and 3G, slowly but steadily taking over, provides improved capacity and bandwidth. Several telematic and fleet management projects already uses cellular technology (e.g. SMS reports), however the relatively high cost, together with limited bandwidth and latency make it impossible to use as a main communication means.

2) IEEE 802.11p based technology: IEEE is working on a variation of 802.11 standard that would be applied to support communication between vehicles and the roadside, or, alternatively, among vehicles themselves, operating at speeds up to 200 km/h, handling communication ranges as high as 1,000 meters. PHY and MAC layers are based on IEEE 802.11a, shifted to the 5.9 GHz band (5.850-5.925 GHz within US). The technology is promoted by the car industry both in Europe (Car2Car CC) and US (VSCC, VII). Estimated deployment cost is foreseen to be relatively low due to large production volumes.

3) Combined wireless access: One of the most significant efforts in combining those wireless access technologies is done by ISO TC 204 WG16, called CALM M5 (Continuous Air Interface for Long and Medium range). It builds on the top of IEEE 802.11p, incorporating a set of additional interface protocols. Currently supported standards include: Cellular Systems: GSM/HSCSD/GPRS (2/2.5G) and UMTS (3G), Infrared Communication and wireless systems in 60 GHz band. Using all those interfaces in a single, uniform system would result in increased flexibility and redundancy, thus improving applications' performance. Apart from interoperability issues, CALM is also engaged in the standardization of the protocols, network layer and the management services.

B. Spectrum issues

The intended usage period for V2V communication system is estimated for at least 20 years and within this time the spectrum availability has to be guaranteed. In the US the FCC has already allocated 75 MHz of spectrum at 5.9 GHz (from 5.850 to 5.925 GHz) for C2C and C2I communications. As agreed by VSC and VII Consortiums, the best technology available for the communications systems using this spectrum would be a derivative of IEEE 802.11. Thus the already mentioned development of the IEEE 802.11p and ISO TC204.

Unfortunately a continuous spectrum of 75 MHz in DSRC band is not availablein Europe. Hence the Car2Car CC has proposed a derivative of the US approach. The proposal allocates 2 x 10 MHz for primary use of safety critical applications at 5.9 GHz range (5.875 - 5.925 GHz). This band is used as control channel in the US, and its allocation in Europe would allow for world-wide harmonization. The same technology would then allow using additional spectrum at either in the 5 GHz RLAN band or in the 5.8 GHz IRM band for non-safety critical and commercial applications [17]. The 5.9 GHz band is currently allocated for military radar systems and fixed satellite services; however recently the CEPT/ECC Short Range Device Maintenance Group (SRD/MG) has recommended placing the 10 MHz control channel in 5.885 - 5.895 GHz, to align with the US approach, and the second 10 MHz channel in the upper part of the ISM band (5.865 - 5.875 GHz) to take also into account radiolocation services below 5.85 GHz.

C. Broadcasting and message dissemination

The foreseen applications will require a vast amount of information to be broadcasted, thus several broadcasting techniques are taken into account. That includes some narrow bandwidth solutions like FM radio (used for RDS/TMC), but also wider bandwidth digital services such as DAB, DVB, DVB-H, S-DMB, T-DMB and DDB. Satellite broadcasting also emerges as a possible solution, as it already includes real-time traffic information services [15].

Broadcasting appears to be an attractive solution due to its low cost and large potential volumes of data. There are already some services available that, based on DAB broadcast and TPEG protocol, offer real-time traffic information.

Location-aware broadcasting would limit the broadcast range only to the site of interest, thus reducing overhead (avoiding the broadcast storm problem). Clustering is another approach to optimize the message dissemination process: neighbor nodes form clusters, manageable units that limit the broadcasting range. E.g. in [1] a clustering method called Local Peer Groups (LPGs) is proposed, where nodes can either form static or dynamic clusters.

D. Routing issues

MANET routing protocols have brought a lot of attention during the last years, however in case of vehicular networking certain network characteristics make these protocols unsuitable. This is due to main MANET routing assumption: intermediate nodes can be found between source and destination and end-to-end connection can always be established. But frequent network partitioning in VANETs requires a different approach, e.g. the 'carry and forward' idea [2], where, if no direct route exists, a packed is carried by a node until it could be forwarded to a node being closer to the destination. The 'carry and forward' concept can be combined with one of the 3 main routing algorithm categories suitable for VANETs: opportunistic forwarding [3], trajectory based forwarding [4] and geographic forwarding [5]. Also a hybrid solution, mixing 2 or 3 different approaches, could be developed. In opportunistic forwarding, a message is stored and forwarded whenever given the opportunity. This algorithm works efficient in broadcasting mode, but fails when the target is a single node. Some analysis of message dissemination on top of opportunistic forwarding can be found in [6]. Geographic forwarding and trajectory forwarding work similarly in the context of VANETs, as vehicular traffic follows the road layout. In the first case (e.g. GFG/GPSR, [5]) packets are forwarded towards the destination based on node geographical location. That approach offers good scalability, but is problematic with dead-ends and voids even if a path towards a destination exists (perimeter routing partially solves the problem). In trajectory routing the road infrastructure serves as an overlay directed graph, with intersections seen as graph nodes and roads as graph edges. Messages move following predefined trajectories and distance is defined as a graph distance (unlike in the case of geographic forwarding, where a simple Cartesian distance is used). Trajectory routing could be seen as the most natural message forwarding algorithm for VANET networks.

E. Power management

Power management in VANET is not concerned about energy efficiency, but rather about the transmission power - when too high, the ongoing transmission could disrupt another transmission at a distant node due to interferences. Thus the denser the network is, the lesser TX power should be used. This issue is also important from the routing point of view: how to adjust the transmission power to maximize the overall throughput, minimizing interferences? Several algorithms could be employed here, e.g. in [7] the power is adjusted to keep the number of neighbors within the max and min thresholds. On the other hand [8] concentrates on improving the 1-hop broadcast coverage by TX power adjustments; however in this study nodes are static and all of them use the same TX power (it was adjusted per all nodes).

F. Security and Privacy

Security is an issue that needs to be carefully assessed and addressed in the design of the vehicular communication system. Several threats potentially exist, including fake messages causing disruption of traffic or even danger, compromising drivers' private information, etc. The issues to be addressed include trust (vehicles are able to trust the messages they receive), resiliency (resiliency for interference, easy maintenance) and efficiency, e.g. real-time message authentication.

Privacy is also a major issue that will need to be addressed. Anonymity must be preserved - the communications should not make the vehicle tracking or identification possible for non-trusted parties. The lack of taking into account the privacy concerns at the early design stage could result in multiple law suits after the network is deployed.

If, as it is in the networking world, each node (vehicle) would carry a unique, permanent MAC address, then it could be possible to trace such a car and its driver. For that reason IEEE 802.11p introduces dynamically assigned MAC addresses, along with a mechanism for duplicate MAC address discovery.

G. VANET modeling and simulation

Road traffic has certain properties that can not be easily modeled in a straight-forward way, using the classical MANET approach. Vehicles do not move randomly but rather follow the road infrastructure; road signs, traffic lights and other cars influence nodes' behavior. Nodes move at high relative speed, network density changes very dynamically, depending on location, recent events (e.g. accidents) or time of day. Thus, one could either build a sophisticated road traffic mobility model on top of some popular network simulator (NS-2, OPNET, GloMoSim), or use mobility traces from another source. This could be either measurement-based road traffic traces or traces obtained from a third party vehicular traffic simulator (e.g. CORSIM, VISSIM). An interesting attempt has been made in [9], where authors managed to interlink NS-2 simulator with VISSIM, a vehicular traffic simulator, together with application simulator based on Matlab/Simulink environment. This approach gives one more opportunity - a chance to observe how the VANET functionality affects the drivers' behavior, hence influencing the network parameters. Yet this solution is not optimal from efficiency point of view: instead of 3 different environments (running on different operating systems), having a single, uniform simulation environment with network, vehicular traffic and driver behavior models would improve computational efficiency and decrease complexity.

IV. Economic issues

The Car-to-Car Communication technology bears direct network effects, i.e. to be able to profit from it, first a certain

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market penetration is required. Therefore a cooperation among car manufacturers and even other parties such as government agencies is a must. It appears that when perceiving the C2CC technology as a platform for a variety of applications, different user groups, of which some are looking for specific solution to their problems today, can be satisfied [10].

There are two mechanisms that lead to a successful market introduction for consumer technologies: either there is a visible added value of the technology for the customer or a regulative order that does not leave alternatives, requires its use.

The problem with a regulative introduction is that, to be issued, the effectiveness of the technology has to be proven first. But in case of car-to-car communications, a certain market penetration is required before any effects or improvements can be shown. Hence, it cannot be expected that a regulative order is issued on the basis of promised safety and traffic flow improvements before the penetration is reached. The car-to-car communications market is thus unlikely to be driven by such a force. And for the added value there raises another problem: when a consumer can only take advantage of a technology once a certain market penetration is reached, no one will invest in this technology before this is the case, which again means that this penetration might never occur. It was estimated that in order to make the network usable, at least penetration of 10% is needed. Provided that 50% of all newly produced cars are C2CC enabled, reaching that 10% should take about three years. In comparison, company cars are resold in average after about 2.5 years. The respective owner would thus resell a car with a technology he never had the chance of profiting from. And 10% equipment rate has been mentioned here just as a lower bound. [10]

The strategic idea is to introduce C2CC with help of Car-to-Infrastructure Communication (C2IC) applications, which cover also the areas of comfort and infotainment. The communication with infrastructure has the advantage that the fixed nodes can be installed independently from the market penetration rate. That way all the users could get some functionality right from the start. The system should be divided into basic C2CC functions, which is integrated in all vehicles, and optional C2IC applications. C2CC applications can be sold only once the required penetration rates are reached.

Despite all the problems, there is a potential to successful introduction of the C2CC technology into the market. It requires though that all the interested players are coordinated, so that they can base their concept on the VANET platform and take fair part in the market acquisition. The respective harmonization should be brought about as soon as possible.

V. Current projects and standardization

The following section shortly explains main characteristics of the standardization process and research projects initiatives, focusing on current developments in Europe, US and Japan. It is foreseen that these solutions will eventually converge, leading to a common, worldwide VANET platform.

A. Europe

There were several projects held in Europe, joining partners from the industry, governmental agencies and academia. Topics covered within these activities include (among others) hazard warnings triggered by hazard flashers, elaborated within Inter-Vehicle Hazard Warning project (IVHW); cooperative driving which was addressed in CarTALK 2000, PROMOTE-Chauffeur and INVENT VLA projects, and driver information and warning issues addressed by PReVENT WILLWARN, SAFESPOT and FleetNet (extended in NoW and Car2Car CC). Currently the three top-priority challenges in Europe are: frequency allocation, protocol definition and infrastructure deployment. As for now it has been agreed to use a frequency spectrum for vehicular safety applications similar to the US (fraction of the DSRC band). Also adaptation of US/international protocols should be applied wherever possible.

Network on Wheels [11] is an ongoing (2004 - 2008) German research project funded by the German government. Its main partners include academia, automotive and IT industries. NoW aims at designing widely defined communication system, including various functionalities from earlier EU projects (based mostly on the FleetNet project). Standardization is to be done on European level in cooperation with the Car2Car CC. Radio system is based on IEEE 802.11 adapted to European market.

The Car2Car Communication Consortium [12] is a non-profit organization initiated by European vehicle manufacturers in 2004, pushing for further increase of road traffic safety. Its mission is to create an open European industry standard for Car2Car communication systems based on wireless LAN components and guarantee European-wide inter-vehicle operability. That includes proposing of realistic deployment strategies and business models to speed-up the market penetration.

B. USA - VSCC and IEEE 802.11p WG

Since 2002 the Vehicle Safety Communication Consortium (VSC) has been working on the development of DSRC standards, protocols and applications, applying inter-vehicle and road-to-vehicle communications. System proposals for the near future include traffic violation warning, curve speed warning and emergency electronic brake lights. Middle future proposals include pre-crash sensing (prepares for unavoidable collisions), lane change and cooperative forward collision warnings, left-turn and stop sign assistance.

VSC Consortium decided to adapt an existing IEEE 802.11 WLAN standard. Namely it incorporated 802.11a PHY layer, using orthogonal frequency division multiplex (OFDM) as well as MAC layer, CSMA/CA, with some adjustments. It operates in 5.9 GHz DSRC band, consisting of seven 10 MHz channels, one of which is assigned for C2CC [13].

IEEE 802.11p, also referred to as Wireless Access for the Vehicular Environment (WAVE) defines enhancements to IEEE 802.11 required to support Intelligent Transportation Systems (ITS) applications. This includes data exchange between high-speed vehicles and between vehicles and the

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roadside infrastructure in the 5.9 GHz band (5.85-5.925 GHz). It will be used as the groundwork for DSRC (Dedicated Short Range Communications), a US Department of Transportation project, looking at vehicle-based communication networks, particularly for applications such as toll collection, vehicle safety services, and commerce transactions via cars.

The 802.11p Task Group is still active. Per the official IEEE 802.11 Work Plan predictions the formal 802.11p standard is scheduled to be published in March 2008. The WAVE technology is often referred to as WLAN or CALM M5 in the subsequent documents, although the CALM acronym (Continuous Air Interface for Long and Medium range) originates from ISO TC204 WG 16 [14], [15].

C. Japan - AHS and ASV [16], [14]

The situation in Japan regarding the development and deployment of Co-operative Systems is more complex. Mainly because Japan is more technologically advanced than US or EU countries, thus there is already a very large installed base of in-vehicle systems with navigation (mostly VICS, real-time traffic and travel information service) and Electronic Toll Collection (ETC) on-board units [16]. In the Japanese approach the public sector builds the basic services for information and safety, which makes buying the on-board unit more attractive. The announced plan for the 2nd Stage of ITS Deployment (2007) is based on the concept of Universal On-Board Unit, on which all the services are based.

There are two main initiatives regarding vehicle co-operative systems: one is vehicle-based (ASV) and the other infrastructure-based (AHS). These are driven by the Ministry of Land, Infrastructure and Transportation (MLIT). The initiative aiming at combining both of these is called Smartway. The word smartway symbolizes a road or highway which enables a wide range of information to be exchanged among all its users, creating a platform for ITS services. The Smartway project consists of several systems communicating between the road and the vehicles, and a variety of sensors, like short and mid-range radars, cameras, ultrasound, infrared and others.

ASV stands for an Advanced Safety Vehicle and builds on C2CC. Its current generation is ASV-3. AHS stands for Advanced Highway Systems, and is promoted by Advanced Cruise-Assist Highway System Research Association (ASHRA). AHS is based on similar technologies to those of ASV, but unlike the ASV, it is concerned only with C2IC.

For the time being the level of co-operation and integration between ASV and AHS programs is not known yet. Neither is it clear if their components will be promoted individually, or under the Smartway concept. However, it has already been decided to assign the 5.9 GHz DSRC band for vehicular communication in Japan.

VI. Summary

We have listed here some of the open research challenges that need to be addressed in order to complete the standardization process, adapting the system to VANET requirements. Also economical, legal and institutional issues remain unresolved. After they are dealt with, the deployment phase would start, and the system could become fully functional within a few years, after certain market penetration is reached and sufficient roadside infrastructure built. The technology promoted by the car industry both in the US (VSC Consortium, VII Initiative) and Europe (Car2Car Communication Consortium), will inevitably lead to one universal standard, based on WLAN / CALM M5 / IEEE 802.11p, a vehicular version of the IEEE 802.11 WLAN technology. Although the IEEE 802.11 standards family was initially developed for the use of laptops and PDAs in hot-spots, it is relatively easily converted for vehicular use, moving to a different, licensed frequency band, common for all participating countries. The main benefit of this technology is that it would be cheap, due to large volumes, thus making the deployment easier, further accelerating the market penetration.

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