A HYBRID SOLUTION FOR VEHICULAR COMMUNICATIONS

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ABSTRACT

Wireless Access in Vehicular Environments (WAVE) and Universal Mobile Telecommunication System (UMTS) are two technologies that can be used for vehicular communication. WAVE realizes Car-to-X (C2X) communication with WLAN based ad-hoc networks of vehicles and roadside infrastructure. UMTS is a state-of-the art technology for mobile communication and offers a cellular infrastructure based solution. This paper presents a comparative study of these two technologies and reveals that they are complementary to each other in supporting vehicular applications. We also propose a hybrid solution combining both WAVE and UMTS technologies to optimize the performance of the vehicular communication system, to increase the market penetration rate and to reduce the deployment costs.

KEYWORDS

Vehicular Communication, WAVE, UMTS, Hybrid Solution, Car-to-Car, Car-to-X

I INTRODUCTION

Wireless communication technologies enabling vehicles to communicate to each other and to a roadside infrastructure play an important role in the Intelligent Transportation System (ITS). Especially communication supported driver assistance systems are expected to improve traffic safety and efficiency significantly. So far, most studies on vehicular communication focus on the Wireless Local Area Network (WLAN) based Car-to-Car (C2C) and Car-to-X (C2X) communication, e.g. the IEEE Wireless Access in Vehicular Environments (WAVE) system. WAVE is able to provide broadband local communications with low latency, which is mandatory for realizing vehicular active safety applications, such as wireless local hazard warnings, vehicle maneuvering assistance and cooperative automatic cruise control. Studies have shown that, if the required minimum market penetration rate is reached and the Road Side Unit (RSU) infrastructure is available, WAVE can satisfy the communication requirements of safety and non-safety applications in most cases, such as on the highway [13] and in a city, under over-crowded and sparse traffic conditions [15]. One major step towards WAVE technology on the road was the spectrum allocations of 75 MHz ITS band at 5.9 GHz in the U.S. in 1999. In 2008, the central 30 MHz of the U.S. ITS frequency band also got approved in EU. However, another important step towards the market introduction will be the availability of a crucial number of RSUs, which is a prerequisite for the successful introduction of the service.

In addition to this newly developed, specialized vehicle communication technology, the cellular technologies like the General Packet Radio Service (GPRS) and the Universal Mobile Telecommunications System (UMTS) offer data services with infrastructure based communication and are widely developed across Europe. Using cellular communication systems for vehicular safety and non-safety applications has been investigated in the German Cooperative Cars (CoCar) project [1]. According to the project results, UMTS provides efficient means to realize the majority of applications in the area of traffic safety and efficiency. Even safety relevant applications like traffic hazard warnings can be realized with transmission delays below one second. However, it is also observed that the communication delay and the system capacity of current cellular networks cannot fulfil the requirements of extremely time critical or capacity consuming safety applications, e.g. vehicle manoeuvring services.

In this study we compare WAVE with UMTS regarding the support of vehicular applications, and reveal that these two technologies are complementary to each other. Furthermore, we propose a hybrid solution combing WAVE and UMTS. Benefiting from the complementary features of both technologies, the hybrid solution can improve the overall system performance.

This paper is organized as follows: in section II we briefly review the WAVE and the UMTS technologies. The comparison between WAVE and UMTS for vehicular applications is presented in section III. In section IV, we propose the hybrid solution, which can address the drawbacks of each technology by using the advantages of the other. Section V gives the simulative study of the proposed hybrid solution using the Traffic Message Dissemination (TMD) in urban scenario as an example application. Section VI concludes the paper with suggestions to the deployment of vehicular communication system in Europe.

II WIRELESS ACCESS IN VEHICULAR ENVIRONMENTS (WAVE) AND UNIVERSAL MOBIL TELECOMMUNICATIONS SYSTEM (UMTS)

WAVE

The WAVE system is designed to operate on the dedicated frequency bands at 5.9 GHz with 10 MHz or optionally 20 MHz channel spacing. On-Board Units (OBUs) and RSUs are the basic building blocks in the WAVE system, which can rapidly establish a WLAN involving no association and authentication [7]. Figure 1 shows the WAVE communication patterns, where an OBU can exchange information with other OBUs or RSUs through the wireless interface specified by WAVE standards.

The protocol architecture of WAVE system is illustrated in Figure 2. The Physical (PHY) layer and the basic Medium Access Control (MAC) layer are specified in IEEE 802.11p standard and all higher protocol layers are described by the IEEE 1609 standard family.

The PHY of WAVE is based on the IEEE 802.11a standard using OFDM technology. With a frequency channel spacing of 10 MHz, WAVE can support a data rate up to 27 Mb/s. To allow for longer communication distance up to 1 km, the maximum radio output power is 760 mW. The basic MAC protocol of WAVE uses IEEE 802.11 Distributed Coordination Function (DCF) that is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. The WAVE MAC extension layer, as specified in IEEE 1609.4, adopts the Enhanced Distributed Channel Access (EDCA) of 802.11e, which is meant for the distributed QoS support in IEEE 802.11 WLAN.

For safety applications, which usually require a point to multi-point communication, the networking issue is copped with the novel WAVE Short Message Protocol (WSMP) introduced by IEEE 1609.3 standard [4]. WSMP provides efficient broadcast service with low latency. As far as multi-hop communication is concerned, routing becomes a challenging issue because of the dynamically changing network topology of Vehicular Ad-hoc Networks (VANET). As surveyed in [5], location and geographic information based routing algorithms, known as position based routing and geocast routing, are usually used in VANET.

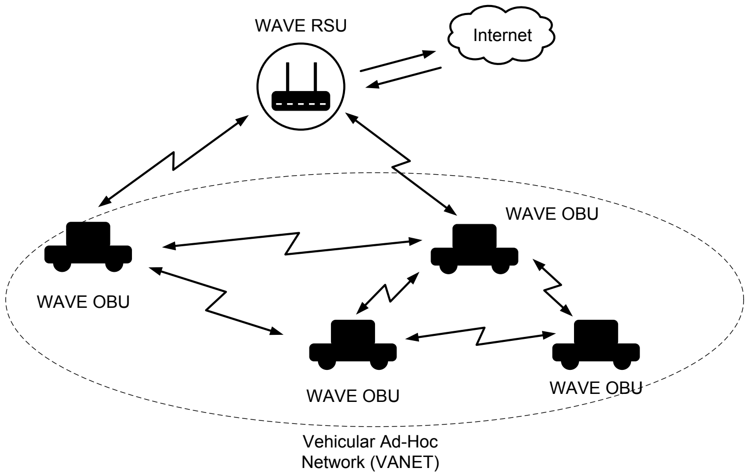


Figure 1: Communication Pattern of Vehicular Applications in WAVE System

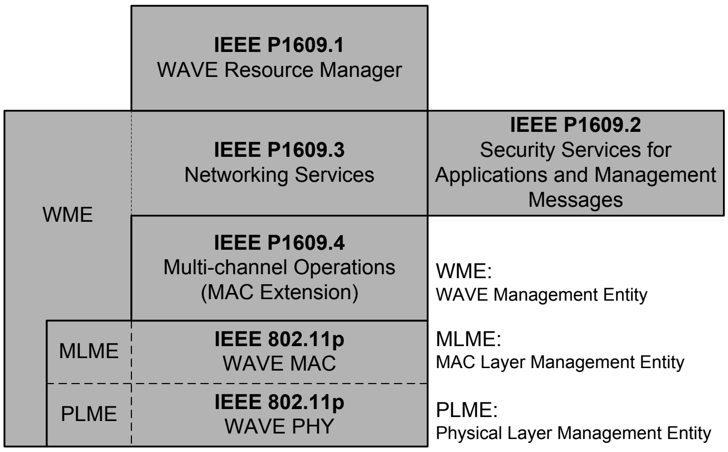


Figure 2: WAVE Protocol Structure

UMTS

Unlike direct communication in WAVE ad-hoc networks, UMTS terminals communicate to each other via a central infrastructure. The common communication pattern of vehicular applications using UMTS relies on an uplink message that is sent out by a vehicle and transmitted via the UMTS network to a central server attached to the network. There, the information is processed and addressed through the downlink to a certain group of vehicles that are in the geographical area of relevance. The rough message flow is shown in Figure 3, whereas sending and receiving cars may be in the same or different cells.

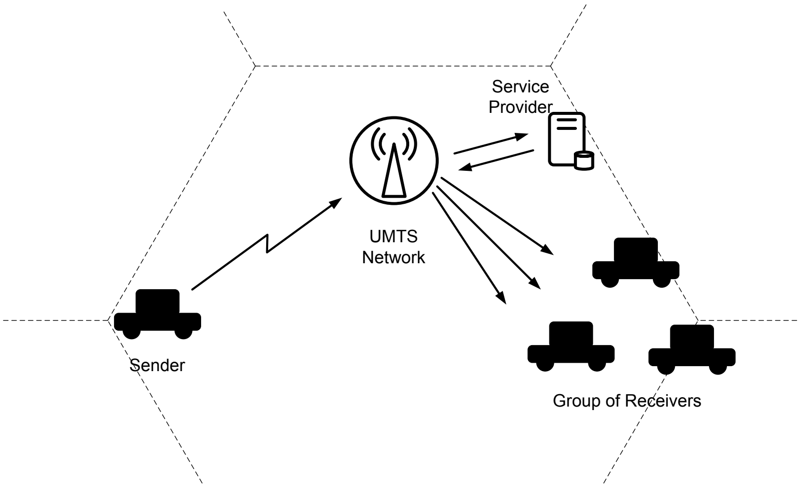


Figure 3: Communication Pattern of Vehicle Application Using UMTS

Vehicular applications, e.g. the traffic jam warning and the bad road condition warning, employ a point-to-multi-point communication, i.e., the information addresses a group of vehicles in the geographical area of relevance. According to the performance study in [11], many of these applications can be realized with today's UMTS networks already. In addition, assuming large numbers of users the most effective way to realize such kind of applications is to use the geo-scalable and geo-specific broadcast services provided in the cellular systems for message dissemination. Cell Broadcast Service (CBS) and the advanced Multimedia Broadcast Multicast Service (MBMS) are the broadcast services standardized in UMTS, which enable the network operators to broadcast messages to user equipments in a given geographical area. In comparison with CBS, MBMS can provide more sophisticated broadcast and multicast services with much lower transmission delay. Therefore MBMS is preferred for vehicular applications. [17]

According to he technical feasibility study in [17] traffic warnings with UMTS achieve an average transmission delay of about 300 ms. Furthermore, employing MBMS for message dissemination leads to vehicle-to-vehicle delays of about 500 ms.

III COMPARISON BETWEEN WAVE AND UMTS FOR VEHICULAR APPLICATIONS

In this section, WAVE and UMTS are compared with respect to network structure, communication range, delay performance and network capacity.

Network Structure and Communication Range

As a typical ad-hoc network, the WAVE system can work for inter-vehicle communication without pre-established infrastructure. The flexible network structure and the limited communication range make the WAVE technology perfect for local communications in an ad-hoc mode, e.g. for the wireless local hazard warning application. However, infrastructure is still needed for applications involving vehicle-to-roadside communication and for maintaining communication security [8]. Due to the lack of roadside infrastructure, WAVE technology is foreseen in Europe mainly for safety and telematics services using C2C communication. However, to realize transmissions over large distances, with C2C communication needs multi-hop transmissions, which is relatively difficult due to the frequently changing network topology and vehicle density in VANET.

On the contrary, the UMTS network is based on a well developed infrastructure with significant coverage in Europe. The infrastructure based network provides efficient information dissemination over a large distance, owing to the core network infrastructure. The network also supports user authentication, high mobility, and security. However, all communications in cellular systems have to go through the core network, and no direct communication is possible among mobile terminals. This lack of direct communication among mobile terminals limits performance to a certain extend. E.g. today's UMTS networks offer round trip times around 100 ms, whereas the transmission delay between two WLAN ad-hoc terminals is typically below 10 ms of one single hop. This means that especially for short range safety services direct C2C communication is preferred.

Transmission Delay

In WAVE system, the end-to-end delay consists of the communication delay and the information processing delay. The information processing delay is considered to be constant at each hop, whereas the communication delay may vary dramatically according to the network density and the traffic load on the wireless channel. Measurements in [9] and [12] show that the average end to end communication delay of WLAN devices is on the order of millisecond. This matches the delay requirement of safety relevant services very well. However, the study in [15] reveals that in a crowded WAVE system the communication delay of safety service increases, when the wireless channel gets busy because of interference. Unless the channel get extremely busy, which can be avoided using elaborated communication protocols [16], the message propagation delay using inter-vehicle communication can always satisfy the requirement of safety services, given the sufficient market penetration rate. In case of low market penetration, WAVE communication suffers from a network disconnection problem that induces unacceptable communication delays [10]. From this point of view, the market penetration heavily impacts the performance of WAVE based C2C communication network. Therefore, a solution is needed to speed up the penetration of WAVE devices, especially during the market roll-out phase.

As summarized in [17], to implement the hazard warning applications in today's UMTS networks, the approach using common transport channels is preferred. This enables an average vehicle-to-vehicle transmission delay about 300 ms for a hazard warning introduction scenario. For higher service penetrations, MBMS is a more resource efficient way to distribute the warning message because it can address a group of receivers at the same time. MBMS with UMTS can provide an average vehicle-to-vehicle transmission delay of 500 ms. On the contrary to the WAVE system, as long as the coverage of UMTS networks is available, the delay performance of UMTS network is more or less independent from the penetration of user terminals because of the wired backbone infrastructure.

Network Capacity

In WAVE system, the given bandwidth is shared by multiple users located in the interference range of each other. The contention based Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme is employed to coordinate the channel access. With increasing number of users that contend for the channel access, the probability of package collisions increases accordingly. Therefore, the WAVE system is a collision limited system, and under the overloaded situation, which is considered as the worst case of the system, the performance of WAVE system depends very much on the number of users [3]. Nevertheless, the studies in [16] show that by differentiating and managing the priority of messages being transmitted, we can prevent the system being overloaded, and therefore, to guarantee the QoS of the WAVE system.

The capacity limitation of UMTS system has been studied in [11]. E.g. for UMTS Release 99 networks, it is stated that for the vehicular safety applications like traffic warnings, inducing only small (< 100 B) and rather rare transmissions, the WCDMA system will be code limited, which means that the maximum number of users that can be served depends on the number of available codes in the network. This means that in UMTS Release 99 a maximum of 251 vehicle terminals per cell can be served with a dedicated network connection, given no code resource is allocated to any other UMTS services. In case of more frequent transmissions, additional services or larger data packets, the interference will limit the system capacity to even less communicating vehicles. This constrains the ability of UMTS in supporting vehicle manoeuvring service, which needs dedicated data communication to every vehicle.

One conclusion of the evaluation in [11] is that today's UMTS networks allow the introduction of warning services. However, for a large scale deployment of cooperative applications, the use of broadcast services, e.g. MBMS, is proposed to enhance system capacity addressing multiple terminals simultaneously.

Table 1 summarizes the pros and cons of each technology in a comparative view.

Table 1: Comparison between UMTS and WAVE for Vehicular Applications

	UMTS	WAVE
Network Infrastructure	Infrastructure based system	Infrastructure-less system, but some services require infrastructure support
	Infrastructure available	No infrastructure available in Europe
Communication Range	Large network coverage range	Ad-hoc network with single hop distance of 300 m to 1 km
Processing and Network Delay	Minimum end-to-end delay around 100 ms for local hazard warning service, but not guaranteed	Guaranteed minimum end-to-end delay < 100 ms for local hazard warning
	Delay performance of long distance communication is independent of penetration rate	Delay performance of long distance communication depends on the penetration rate
System Capacity	Interference limited system with constrained number of codes in each cell	Contention-based system; The system saturation throughput is limited by the number of active users
Cost	Licensed spectrum	License-free spectrum
	Well developed network reduces the cost of developing and maintaining the infrastructure	Huge investment is expected in deploying and maintaining the roadside infrastructure
Security and Anonymity	Centralized	Distributed protocol relying on infrastructure

: Pros : Cons

IV PROPOSAL OF HYBRID SOLUTION

Through the comparative analysis, we can see that the ad hoc WAVE system and the infrastructure based UMTS network are complementary to each other in many aspects. This motivates us to investigate the combination of both technologies into a hybrid solution, so that we can benefit from the advantages of one technology and address the drawbacks of the other. Besides, the hybrid solution is also based on the following considerations:

- The vehicular applications supported by both technologies are the same, including safety relevant, telematics and infotainment services.
- The frequency bands for UMTS cellular networks and for the ad-hoc WAVE system are separated with sufficient guard bandwidth, which makes the coexistence of both technologies in a single user device feasible.
- The WAVE radio module is cheap and mature, as it is physically identical to the prevailing IEEE 802.11a WLAN products on the market.
- UMTS system is used for both, conventional and vehicular applications. This means that maybe existing networks have to be enhanced with capacity (additional sites and/or broadcast systems) but no dedicated network needs to be deployed.

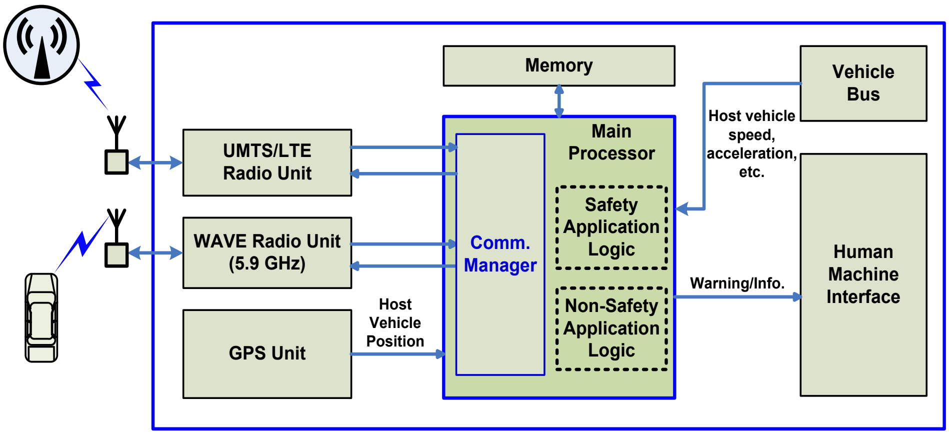


Figure 4: The Block Diagram of Hybrid User Device for Hybrid Solution

The main idea of the proposed hybrid solution is to integrate both WAVE and UMTS radio modules into a single device and let them work simultaneously. The warning message can be disseminated via either or both technologies. So that, on the one hand, WAVE is used for the local hazard warning application that requires extremely low latency. On the other hand, the message can be disseminated rapidly within a large area using the broadcast service in UMTS. Figure 4 gives the system diagram of the proposed hybrid user device, where a 5.9 GHz WAVE radio module collocates with the UMTS radio module in a single device. Other blocks required by vehicular applications are shared by these two radio modules, e.g. the interface to the vehicle bus to get vehicle dynamic data, the human machine interface for interacting with drivers, the GPS unit to get geographic location and timing reference, as well as the application logics for both safety and non-safety services.

In order to combine these two technologies, the proposed hybrid solution introduces a communication manager to coordinate the WAVE and the UMTS radio modules, e.g. to collect and resolve the received messages from them, as well as to dispatch messages to either or both of them for transmission. Intelligent coordination algorithms may be implemented in the communication manager, in order to reach the optimal complementary effect of both technologies.

V SIMULATIVE STUDY OF THE HYBRID SOLUTION

In this section we use stochastic simulations to prove the concept of the hybrid solution. As example application, we select the Traffic Message Dissemination (TMD) of a hazard warning message in an urban scenario. The goal of TMD is to disseminate the traffic messages generated by one vehicle to all other vehicles within the scenario. The concerned metric is the message reception delay with respect to different penetration rates of WAVE, UMTS and hybrid solution users, respectively.

Simulation Scenario and Parameter Settings

In this work we use the Wireless Access Radio Protocol II (WARP2) simulation environment developed at the Department of Communication Networks (ComNets), RWTH Aachen University [14].

In order to perform the WAVE system level simulations, the communication protocol stack is implemented according to IEEE 802.11p and IEEE 1609.3/.4 (draft) standards. Table 2 lists the parameters of the WAVE communication system used in this simulation.

Table 2: WAVE Parameters

Parameter	Value
Channel Spacing	10 MHz
IEEE 802.11p PHY Mode	BPSK ½ (3 MB/s)
TX Power	100 mW
Access Category (QoS)	3 (the highest priority)

In order to simulate the performance of UMTS broadcast, we built a stochastic model based on the system level simulation results of broadcast services in UMTS conducted in [6], which used the NS-2 simulator. The study performed in [6] gives transmission delays of CBS and MBMS message distribution for different network configurations. For this study, we used the results of a CBS simulation in [6] as an approximation for the vehicle-to-vehicle transmission delay in UMTS. However, in practice either unicast transmission or MBMS should be chosen for a large scale deployment to reach better system capacity and consistent performance. [17] Based on the above mentioned assumptions and simplifications, the vehicle-to-vehicle delay for TMD in UMTS is shown in Figure 6 (b) [6].

A realistic urban traffic mobility trace file generated using the Generic Mobility Simulation Framework (GMSF) model [2] is employed in this simulation for the vehicle mobility model. In this simulation, totally 420 vehicles are running on the road network of Zurich city within a 3 km×3 km area, which is derived from the Geographical Information System (GIS) of Switzerland.

In order to simulate the TMD application, we randomly select a vehicle in the scenario as the message source, which detects an abnormal event, e.g. bad road conditions or an accident, and periodically generates traffic information message intended to be received by all other vehicles in the scenario. The size of the TMD message is 100 B and the message generation interval is 100 ms. The goal of our study is to survey the message dissemination delay, i.e. the delay between the time the first message is generated and the time a vehicle is informed about the event, using WAVE, UMTS or the proposed hybrid solution with different market penetration rates.

Message Dissemination Algorithms

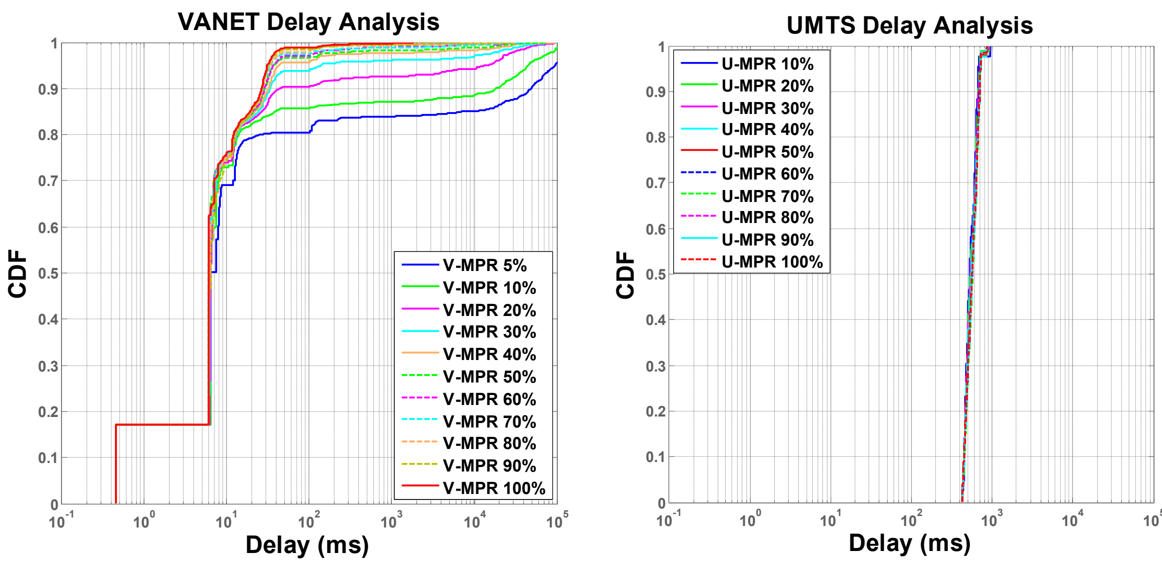
In the WAVE system, a message is disseminated using the message forwarding algorithm introduced in [15]: Each vehicle that receives a new message tries to periodically broadcast it to all its neighbours with a frequency of 10 Hz, until the vehicle hears the same message is broadcast by another vehicle. Then it switches to a lower broadcast frequency, i.e. 1 Hz, in order to keep the message alive in the scenario. The same message with an update timestamp at the traffic source is treated as a new message and will replace the old one.

In the UMTS network, the message is first reported by the traffic source via uplink to the traffic information server located in the UMTS backbone network. All other UMTS users receive the message via the UMTS broadcast service. The delay distribution of the UMTS network is given in Figure 6 (b) [6].

In case of the hybrid solution, a vehicle can receive the message through the WAVE or the UMTS radio interface, and the received message is then further disseminated using the above described algorithms in WAVE and UMTS networks, except that if the message is received through the UMTS interface, it will not be reported again to the UMTS traffic information server but only disseminated using the WAVE interface.

Simulation Results

Figure 5 shows the TMD delay performance using WAVE and UMTS with varying market penetration rate, respectively. From Figure 5 (a) we can see the WAVE based system reaches an acceptable delay performance even with very low market penetration rate (MPR). 96% of the WAVE users can receive the message within 100 s, although only 5% of the vehicles are equipped with WAVE devices. In case all vehicles in the scenario are equipped with WAVE devices, the message can be delivered within one second. One can see in our simulation, half of the WAVE users can receive the message within 8 ms regardless the market penetration rate. This is because the mobility model used in this simulation reproduces a realistic traffic situation in urban scenario, where most vehicles converge to the main streets and, therefore, can contribute to the message dissemination. By contrast, the TMD delay using pure UMTS broadcast, here CBS, in Figure 5 (b), ranges from 400 ms to 1 s and is independent from the penetration rate. This can be explained by the mechanism of the broadcast service, which addresses all subscribed terminals at the same time regardless of the market penetration rate.

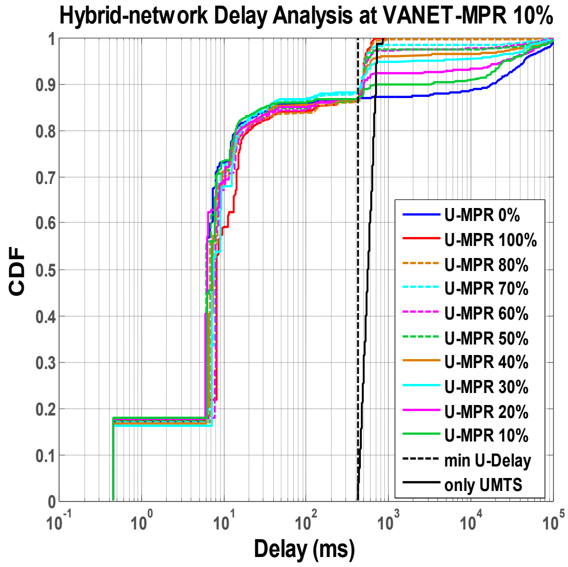


(a) TMD Delay Performance with WAVE

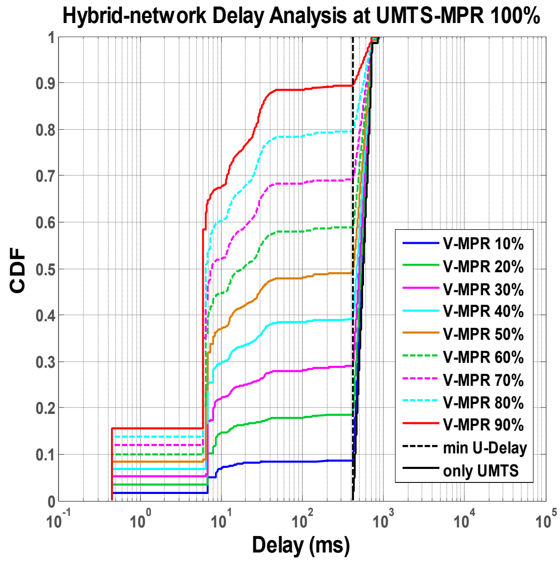
(b) TMD Delay Performance with UMTS Broadcast

Figure 5: TMD Delay Performance with WAVE and UMTS Broadcast

By comparing the performance of WAVE and UMTS broadcast service, we confirmed the analysis in section III regarding the statement that WAVE is efficient in supporting time critical application but its performance depends on the market penetration rate, whereas



(a) Hybrid Devices Improve the Performance of WAVE Network



(b) Hybrid Devices Improve the Performance of UMTS Network

Figure 6: TMD Delay Performance with Hybrid Solution

UMTS is good at message dissemination service offering reliable performance independent from market penetration rate.

In the following, we study the impact of the proposed hybrid solution. To do so, we first fix the penetration rate of WAVE users to 10% out of all vehicles and among those WAVE users we increase the number of hybrid devices from 0% to 100%, marked as *U-MPR* in Figure 6 (a), i.e. from none hybrid user to all users use the hybrid devices. The delay performance is given in Figure 6 (a). For the purpose of comparison, the UMTS delay curve is also plotted as reference, which is marked as *only UMTS*. It is observed that the system works exactly as a standalone WAVE network, until around 400 ms when the message is delivered using UMTS to the hybrid users. From 400 ms on, the delay performance is greatly improved along with the increasing percentage of hybrid users. In case all users use the hybrid devices, i.e. *U-MPR 100%*, the maximum delay is bounded by the delay of UMTS, i.e. around 900 ms. To be emphasized, the UMTS network can not only help the hybrid users but also the WAVE users, who are located in the vicinity of the hybrid users, to improve the delay performance.

Then, we study the effectiveness of the hybrid solution in improving the delay performance in UMTS network. The simulation is performed by setting all vehicles to be UMTS users, and among them we increase the percentage of hybrid users from 10% to 90%, marked as *V-MPR* in Figure 6 (b), and evaluate the delay of the whole system. The results are given in Figure 6 (b). As expected, the maximum system delay is bounded by the UMTS curve, whereas with increasing percentage of hybrid users the minimum delay is improved accordingly. Therefore, we can say, with the hybrid solution the UMTS users can benefit from the integrated WAVE devices in terms of the message transmission delay, especially for safety applications having strict delay requirements.

In addition to the performance improvement presented above, the hybrid solution provides also a way for vehicles to communicate to the Certificate Authorities (CA) located at backbone infrastructure via the UMTS network. This is essential to the security mechanisms of the WAVE based Car-to-Car communication networks, as vehicles need to contact the CAs regularly in order to update or revoke their certificates. [8]

VI CONCLUSION

In this study, we have compared two wireless communication technologies, namely the WAVE based and the UMTS cellular network based C2C communications. The comparison shows that these two technologies are complementary to each other regarding the network infrastructure, communication range, delay performance, as well as system cost. Therefore, we proposed a hybrid solution combining both technologies. Simulation studies show that, on the one hand, the maximum message dissemination delay of WAVE system can be reduced by the hybrid solution and, on the other hand, the hybrid solution can help UMTS users regarding the minimal message transmission delay. Besides, the proposed hybrid solution has the following advantages:

- The infrastructure of cellular systems can serve for both UMTS and WAVE technologies to enable efficient information distribution; it is also helpful to realize WAVE security mechanisms.
- Without additional investment in the WAVE infrastructure, the hybrid device can contribute to the initial WAVE market penetration, which is the prerequisite of a working WAVE C2C system.
- Integrating a WAVE module into the UMTS user equipment might be the most efficient way to improve the local vehicular communication ability for mere cellular users.

As the conclusion, we would suggest that the deployment of vehicular communication system should consider the hybrid solution, which can benefit from the cellular infrastructure from the beginning of the deployment and, in the mean while, can build up the initial penetration rate of the WAVE system.

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REFERENCES

[1] http://www.aktiv-online.org/englisch/aktiv-cocar.html.

[2] Rainer Baumann, Franck Legendre, and Philipp Sommer. Generic mobility simulation framework (GMSF). In *MobilityModels '08: Proceeding of the 1st ACM SIGMOBILE workshop on Mobility models*, pages 49–56, New York, NY, USA, 2008. ACM.

[3] G. Bianchi. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE JSAC*, 18(3):535 – 547, Mar 2000.

[4] IEEE. 1609.3 IEEE trial-use standard for wireless access in vehicular environments (WAVE) - networking services. Technical report, Institute of Electrical and Electronics Engineers, New York, USA, 2007.

[5] Fan Li and Yu Wang. Routing in vehicular ad hoc networks: A survey. *Vehicular Technology Magazine, IEEE*, 2:12 – 22, 2007.

[6] Qiang Mu. Comparison and performance analysis of the cell broadcast service (CBS) and multimedia broadcast multicast service (MBMS) for distribution of road traffic information. Master's thesis, ComNets, RWTH Aachen University, May 2008.

[7] IEEE 802.11 Working Group p. IEEE p802.11ptm/d6.01 draft standard for information technology - telecommunications and information exchange between systems - local and metropolitan area networks - specific requirements - part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 7: Wireless access in vehicular environments. Technical report, Institute of Electrical and Electronics Engineers, New York, USA, 2009.

[8] P. Papadimitratos, L. Buttyan, T. Holczer, E. Schoch, J. Freudiger, M. Raya, Z. Ma, F. Kargl, A. Kung, and J. P. Hubaux. Secure vehicular communication systems: design and architecture - [topics in automotive networking]. 46(11):100–109, November 2008.

[9] A. Santana. Test and validation of selected applications on the basis of vehicle-to-vehicle communication. Master's thesis, ComNets, RWTH Aachen University, 2007.

[10] Martin Schoenhof, Arne Kesting, Martin Treiber, and Dirk Helbing. Coupled vehicle and information flows: Message transport on a dynamic vehicle network. *Physica A: Statistical Mechanics and its Applications*, 363:73–81, April 2006.

[11] Sabine Sories, Joerg Huschke, and Mai-Anh Phan. Delay performance of vehicle safety applications in umts. In *15th World Congress on ITS*, New York, Nov. 2008.

[12] Wewetzer, C.; Caliskan, M.; Meier, K. & Luebke., A. Experimental Evaluation of UMTS and Wireless LAN for Inter-Vehicle Communication ITST 2007: Proceedings of the 7th International Conference on ITS Telecommunications, 2007.

[13] N. Wisitpongphan, Fan Bai, P. Mudalige, V. Sadekar, and O. Tonguz. Routing in sparse vehicular ad hoc wireless networks. *IEEE Journal on Selected Areas in Communications*, 25(8):1538–1556, 2007.

[14] Y. Zang, L. Stibor, G. Orfanos, S. Guo, and H.-J. Reumerman. An error model for inter-vehicle communications in highway scenarios at 5.9GHz. In *Proceedings of the Second ACM International Workshop on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks*, pages 49–56, Montreal, Quebec, Canada, Oct 2005.

[15] Y. Zang, L. Stibor, H.-J. Reumerman, and H. Chen. Wireless local danger warning using inter-vehicle communications in highway scenarios. In *Proceedings of European Wireless Conference 2008*, page 7, Prague, Czech Republic, Jun 2008.

[16] Y. Zang, Lothar Stibor, Hans-Juergen Reumerman, Andre Barroso, Arthur Paruzel, and Xi Cheng. Congestion control in wireless networks for vehicular safety applications. In *Proceeding of European Wireless 2007*, Paris, 2007.

[17] Cooperative Cars, CoCar Feasibility Study – Technology, Business and Dissemination, Public Report by the CoCar Consortium, 2009, http://www.aktiv-online.org/english/downloads/CoCar_D04_%20public.pdf