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Field Operational Tests for Cooperative Systems: A Tussle Between Research, Standardization and Deployment*

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ABSTRACT

After a decade of research and technology development, road cooperative systems based on vehicle-to-vehicle and vehicle-to-roadside infrastructure communication are currently in a trial phase. Major field operational tests (FOTs) are carried out to verify the operation of cooperative systems in real environments and assess the impact of applications on road safety, traffic efficiency as well as driver behavior and user satisfaction. Standards to achieve interoperability are developed and a potential introduction of a cooperative system is prepared.

An FOT is exposed to various requirements from research, standards and deployment that are – at least partially – adverse to each other. We study the dependencies for the case of the DRIVE C2X project, a pan-European FOT for cooperative system. The paper puts the technologies used in the FoT, particularly focusing on communication, into the context of research activities for cooperative systems. We show that the FOT is based on technologies for a minimal cooperative system that is ready to be introduced and sustainably deployed. Further, we identify research concepts and technologies that did not find their way into the basic cooperative system yet and discuss potential directions for future enhancement of the minimal system.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous; C.2.0 [**Computer-Communication Networks**]: General-Data communications

General Terms

Experimentation, standardization, verification

Keywords

Car-to-X, cooperative systems, field-operational tests

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1. INTRODUCTION

Road cooperative systems are commonly regarded as a cornerstone of future Intelligent Transport Systems (ITS) and promises great benefits for drivers and passengers. They are based on vehicle-to-vehicle and vehicle-to-roadside communication. Key technologies include access technologies (in particular IEEE 802.11p operating in the 5GHz band, 3G/4G cellular systems), positioning (GPS), networking (ad hoc and IP), as well as digital maps, management of real-time location-based data management, messaging and security. These technologies enable a wide range of applications for safety, traffic efficiency, infotainment and business applications for cooperative ITS.

Cooperative systems make use of various concepts that were originally developed for other communication systems. Starting from the basic idea of communicating cars, the research on cooperative systems was inspired and driven by other domains, such as mobile ad hoc networks, wireless sensor networks, sensor data fusion and data aggregation, IP mobility, accurate positioning. A series of R&D projects and initiatives [1] have consolidated a technological basis for cooperative systems that inherited many concepts and resulted in field tests to study cooperative systems in realistic environments and larger scale.

In the current phase of the technology cycle of cooperative systems, world-wide major projects are carried for practical evaluation. Specifically in Europe, Field Operational Tests (FOTs) aim at impact assessment of cooperative systems on safety and traffic efficiency. Such FOTs have been initiated on national level, for example the German simTD [2] and the French SCORE@F, as well as at European level. DRIVE C2X is such a pan-European FOT that attempts to create a framework for road-cooperative systems of common technology and methodology. The project verifies the framework, evaluates test results and prepares the deployment of cooperative systems.

In parallel to the execution of the FOTs, standards for cooperative systems are created. In Europe, a mandate to develop a minimum set of standards needed for the deployment of cooperative systems was issued by the European Commission. Supported by this mandate, ETSI TC ITS and CEN TC 278/ISO TC 204 continuously draft and publish standards. Furthermore, stakeholders work on business strategies and form corresponding ecosystems. First products are being designed and evaluated.

The expectations on FOTs for cooperative systems are high. Ideally, an FOT would be based on the recent state of the art in technology. Likewise, an FOT should be fully

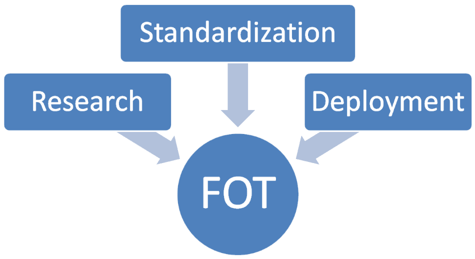

Figure 1: FOT depends on research, standardization and deployment

compliant to the relevant standards for cooperative ITS and exactly represent the system in a future deployment. In reality, research, standards, and deployment do not automatically converge into a unique system.

Certainly, an FOT could be an opportunity to validate latest research results in real environments. But often research ideas, though proved to have excellent performance (typically by simulation), cover only single aspects and their integration into the overall system is not easy. Furthermore, FOTs have strong requirements on the reliability of the system and novel ideas might not be integrated for the sake of simplicity and robustness. As for *standard* compliance, the FOT can only be based on available and mature standards. From the set of standards under development, it needs to take a snapshot, to decide for standards' options during the FOT's system design phase and to make assumptions about future completion of the standards. Further, an FOT validates the implementability of the standards and returns valuable feedback to the standardization process. Finally, an FOT is based on prototypes for evaluation that are designed for robustness and specifically instrumented for impact assessment. Future *deployment* will rather be highly integrated products that always have brand-specific characteristics besides common technology.

Considering the real conditions, an FOT is in-between the triangle *research* – *standards* – *deployment* and must compromise among their adverse requirements.[1] This paper analyzes the trade-off for the case of the DRIVE C2X project and discusses research aspects that are beyond the technologies used in this FOT and how they can be applied to the European cooperative system.

The remaining sections are structured as follows: In Section 2 we give an overview of technologies for cooperative systems, relevant standards and deployment aspects for the case of the DRIVE C2X project. In Section 3 we discuss alternative concepts, algorithms and protocols that are not included in the FOT and analyze their potential for future enhancements. Section 4 concludes the paper.

2. EUROPEAN FOT – DRIVE C2X

DRIVE C2X [4] is a European EC-funded project that carries out the assessment of cooperative systems through FOTs. The project is based on results of the predecessor project PRE-DRIVE C2X.[2] It is associated with the major European national test sites dedicated to cooperative systems: A 'system test site' (STS) in the Netherlands is foreseen for the test framework validation. 'Functional test sites' (FTS) in Finland, France, Germany, Italy, Spain and Sweden execute tests for impact assessment. The 3-years project started in January 2011 and has three main phases: (1) the *FOT framework* phase prepares a technical and methodological framework; (2) the *FOT operations* phase carries out pilot tests on the STS and coordinates the test execution on the FTS; (3) the *FOT evaluation* phase analyzes the data collected by FOT operations.

Safety
Traffic jam ahead warning†
Roadworks warning†
Car breakdown warning†
Approaching emergency vehicle†
Weather warning†
Emergency electronic brake lights†
Slow vehicle warning†
Stop sign violation†
Post crash warning†
Obstacle warning†
Wrong way driving in gas stations†
Motorcycle warning†
Traffic efficiency
In-vehicle signage/speed limit†
Green-light optimal speed advisory†
Traffic information and recommended itinerary†
Infotainment & business
Insurance and financial services⋆
Dealer management⋆
Point of interest notification⋆
Vehicle software provisioning and update⋆
Local electronic commerce⋆
Fleet management⋆

Table 1: Selected applications for FOT evaluation

The project has selected a set of applications for safety, traffic efficiency and infotainment & business (Table 1) that will be evaluated. For the technical basis of road cooperative system, fundamental assumptions are made:

- Operation in the 5.9 GHz frequency band dedicated to safety and traffic efficiency band with a common control channel (CCH) and multiple service channels (SCH)
- IEEE 802.11p PHY and MAC for ad hoc communication with dual-transceivers for multi-channel operation
- 3G cellular networks for communication with a central infrastructure, such as back-end system and traffic management center
- GPS for positioning and time synchronization
- Ad hoc networking for single- and multi-hop communication among vehicles and between vehicles and the roadside infrastructure
- Packet-oriented distribution of information using multihop forwarding

[1] We call this a 'tussle' in analogy to [3].
[2] http://www.pre-drive-c2x.eu

- IPv4 and IPv6 over 3G cellular networks for back-end communication
- Messages for safety and traffic efficiency application, i.e., Cooperative Awareness Message (CAM), Distributed Environmental Notification Message (DENM), Signal Phase and Time (SPAT)
- Database for storage and aggregation of local, real-time information collected by vehicles and road-side units, optionally associated with a digital map
- Secure communication based on digital signatures and certificates
- Privacy protection by means of dynamically changing pseudonyms

In Table 1, applications marked with (†) rely on ad hoc communication over IEEE 802.11p, the applications indicated by (⋆) are based on IP over 3G.

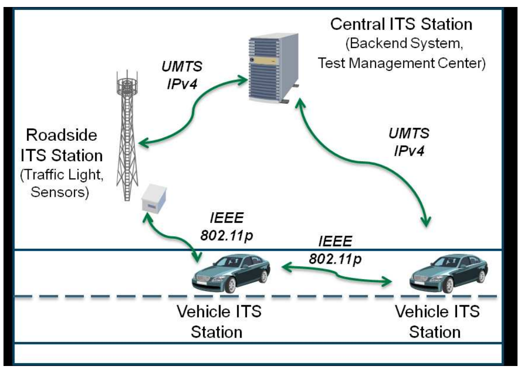

Figure 2: DRIVE C2X architecture

In line with the ITS station architecture [5] the DRIVE C2X system specifies vehicle, road-side and central sub-systems (Figure 2). Vehicle and road-side ITS stations are comprised of a set of common hardware and software components that can be categorized following the layers of the ITS station reference model (Figure 3). The components described below are part of the DRIVE C2X enhanced system, one that considers the latest developments in standardization.

Access technologies comprise of communication and positioning devices for IEEE 802.11p, 3G and GPS with software drivers. Specifically, the IEEE 802.11p device has dual transceivers that operate on the CCH and a SCH, respectively. The interface to the upper layer allows for per packet control of radio parameters, such as channel, data rate, transmit power, etc.

Network and transport realizes two main protocol sets: GeoNetworking with the Basic Transport Protocol (BTP) which enables ad hoc communication among vehicles and between vehicles and roadside units. It supports single-hop (for transmission of periodic messages, i.e., CAM) and multi-hop communication. For the latter it offers geographical addressing, i.e., packet routing to a node or number of nodes within geographical area based on their geographical position. BTP implements a UDP-like transport protocol for multiplexing/demultiplexing of facility-layer messages based on ports. In addition, IPv4/IPv6 forwarding over 3G provides connectivity to the vehicles, roadside and control center for management, testing and logging purposes.

Facilities cover a set of various components:[3] *Message support* realizes generation and processing of basic messages (CAM, DENM). *Position&Time* manages position and time data and provides this information to other components. *Local Dynamic Map* dynamically stores temporal and spatial information over a static digital map. *Vehicle Data Provider* retrieves information from vehicle data buses (CAN bus). The *Human Machine Interface* (HMI) controls the information that is shown to the driver/user. *Service Announcements* are sent by service providers to provide information on how to use/access a certain service, e.g., on which channel the service is provided. The *Back-end Integration Manager* (BIM) allows a vehicle to communicate reliably with a back-end system via a *Vehicle Integration Platform* (VIP) on the back-end side using web services. The *Relevance Checker* supports applications by providing commonly used functions for geographical calculations (e.g., a vehicle drives in the direction of an event).

Management realizes configuration management and cross-layer information exchange of wireless network interface status and events.

Security provides signing, verification and encryption of messages. It generates pseudonyms and control their usage across the protocol stack.

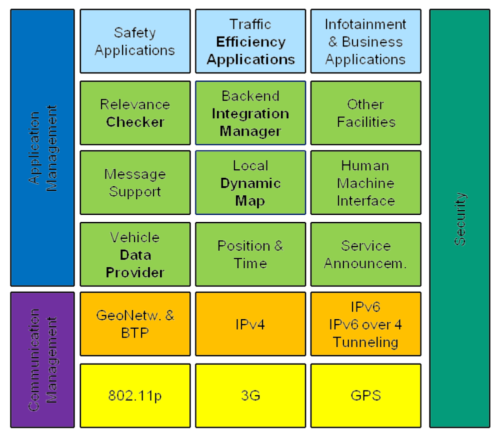

Figure 3: Core technology components

The DRIVE C2X components are compliant to the core standards listed in Table 2. EN 202 663 defines the PHY and MAC layers derived from IEEE 802.11p operating in the 5 GHz band including 5.9 GHz and the RLAN band (ITS-G5A, B and C). EN 302 931 introduces geometric shapes for geographical addressing (circle, rectangle, ellipse) and corresponding geo-spatial relations. TS 102 636 is a multi-part standard that covers GeoNetworking: its part 4 defines the protocol separated into media-independent and media-dependent sub-parts; Part 5-1 specifies a UDP-like transport protocol and part 6-1 the transmission of IPv6 over GeoNetworking. Finally, TS 102 867 derives security services from the IEEE 1609.2 standard, in particular through signatures and certificates for authentication, encryption and others. The European profiles of IEEE 802.11 and IEEE 1609.2 are a result of the ongoing process of international standards harmonization for cooperative systems.

[3]Some components are for vehicles only and not required by road-side units.

Table 2: Core ETSI standards for cooperative ITS used in DRIVE C2X

Standard #	**Standard short title**
EN 202 663	European profile of IEEE 802.11p PHY and MAC
EN 302 931	Geographical area definition
TS 102 636-4-1	GeoNetworking (media-independent functionality)
TS 102 636-5-1	Basic transport protocol BTP
TS 102 636-6-1	IPv6 over GeoNetworking
TS 102 637-2	CAM
TS 102 637-3	DENM
TS 102 867	European profile of IEEE 1609.2 security

The technical equipment developed for the field trial (vehicle on-board and road-side units) is based on embedded systems that meet automotive and road-side infrastructure requirements. The software is modularly designed; components are implemented cooperatively by different vendors and integrated in a common software framework. The prototypes typically use the Linux operating system (or a derivative). Specifically for facilities and applications, the prototypes use the OSGI framework for maximum flexibility of the software. Though being sufficiently mature for field trials, the implemented systems should be regarded as experimental prototypes with a high degree of flexibility and extendability that require further integration towards productization.

For system introduction and deployment, the project investigates ITS-specific and cross-sector business ecosystems and considers the full chain of stakeholder from content and service provider to chip supplier. Introduction scenarios are analyzed from business economics (return on investment) and political economics (cost/benefit analysis) perspectives.

3. TECHNOLOGIES BEYOND THE FOT

Cooperative system technologies implemented in FOTs, such as in DRIVE C2X, leverage result of the research efforts from last years. Nevertheless, there are still open technical aspects where the FOTs do not have mature solutions yet, though they are needed for test operation. Furthermore, various research concepts, algorithms and protocols exist that are not considered in the design of the cooperative system FOT, but may extend the minimal system that surges for deployment. This section analyzes a selection of research aspects for cooperative system. They cover gaps in the current FOT system development and also represent potential long-term extensions for the deployed systems.

Access Technologies play a crucial role in cooperative systems since they establish the elementary communication link that vehicles and roadside infrastructure use to exchange information with each other. A large amount of research has been carried out to improve the communication performance of access technologies for cooperative systems. We discuss most prominent access technologies for cooperative systems below.

CSMA/CA and IEEE 802.11 represent the current main stream of access technologies for cooperative systems. The reason is that IEEE 802.11 is mature, inexpensive, widely available, and well understood. Various modifications for IEEE 802.11 have been suggested, including dynamic adaptation of transmit power and contention window [6, 7] for tuning the communication performance.

Several researchers were not satisfied with the performance of IEEE 802.11 and considered a TDMA-based communication technology for cooperative systems [8, 9]. Since TDMA techniques could offer QoS guarantees and fairness among nodes, they are attractive for cooperative systems where safety applications have high requirements for communication performance. Recent research findings [10] confirmed that TDMA offers better fairness and QoS guarantees but also pointed out that TDMA does not scale as well as CSMA/CA. Further, other issues for TDMA such as fine-grained time synchronization remain unaddressed.

The standard IEEE 1609.4 specifies enhancements for IEEE 802.11 such that single-transceiver interfaces can operate on multiple wireless channels. The standard foresees time synchronization among nodes, a control channel (CCH), and multiple service channels (SCHs). Time is divided into a sequence of CCH and SCH intervals. All nodes have to be present on the CCH during the CCH interval but can switch to the SCHs channels during the SCH intervals. Enhancements for IEEE 1609.4 have been suggested [11, 12, 13] to obtain a better performance of the multi-channel operation and extend the system capacity. In Europe, dual transceivers are considered for cooperative systems (EN 202 663). This approach promises better communication performance at a higher level of implementation complexity. The challenge of an efficient multi-channel operation scheme still remains.

LTE, the long-term evolution for mobile wireless communication, has been touted as the cornerstone of the next generation of mobile Internet. LTE promises high data rates for mobile devices that have now obtained a firm place in our daily life. Assuming a good coverage, it is possible to imagine that future vehicles will be equipped with LTE-capable devices and communicate with others over LTE. Given the time line of deployment and FOT for cooperative systems, it will be difficult to conduct trials for LTE-based cooperative systems in the very near future. Nevertheless, the use of LTE for cooperative systems and its optimization for vehicular scenarios is a research topic that deserves further attention.

Network and transport. In current cooperative systems, network protocols are strictly split into ad hoc routing and IP. For ad hoc routing, various variants have been proposed, for example proactive, reactive, cluster-based or prediction-based. From these GeoNetworking, as implemented in the FOT, appears to be a solid basis for efficient and scalable routing that meets the requirements of safety and traffic efficiency applications. While the FOT still applies a basic scheme of GeoNetworking in line with standardization progress in ETSI TC ITS, the GeoNetworking protocol bears great potential for optimizations: For single-hop broadcast, i.e., transmission of periodic CAM messages sent at high rate, the control of the channel load is commonly accepted in the research community, e.g., [14, 15, 16, 17]. These approaches differ in the metrics (channel load, fairness, message utility, information accuracy) and also in their mechanisms (transmit power, beacon rate, receiver sensitivity). A conclusive evaluation of the schemes is still lacking. For information dissemination with multi-hop routing, advanced forwarding schemes are proposed, in particular utilizing road-topology information for routing, e.g., [18], or contention-based schemes, e.g. [19], but they need further evaluation in combination with optimized single-hop broadcasting schemes.

In the initial deployment of cooperative systems, sparse network scenarios will clearly be dominant and are addressed by few researchers, such as the application of delay-tolerant network concepts to cooperative systems or infrastructure-assisted routing [20, 21]. Current FOTs apply store-and forward techniques, where network nodes temporarily buffer packets and forward when a new neighbor car appears.

With the proliferation of Internet services to vehicles, IP will be used as the de-facto standard, whereas IP version 6 and Network Mobility (NEMO) for IP mobility support is envisioned. The use of standard NEMO (RFC 3965) implies several challenges for vehicular scenarios including address allocation, route optimization, use of geo-information and others [22].

Middleware for cooperative systems is mainly understood as a set of facilities that provide commonly used functions, typically for communication, information and application support. A fundamental function, spread over several those functions, is the information dissemination of safety and traffic-related data in the ad hoc network. It is clear from Sec. 2 and the GeoNetworking-related aspects above that the dissemination strategy in the FOT is principally based on ad hoc packet routing at the network layer. Alternatively to this, a message-based distribution of packets have been proposed by researchers for many years (e.g. [23]).

While packet routing appears to be rather suitable for rapid distribution of information in a geographical area, a message-based scheme facilitates data aggregation and allows for using application knowledge in the forwarding process. In fact, [24] and others suggested a dissemination scheme for information with spatio-temporal scope. While this is regarded as an alternative opposed to the packet-oriented approach, a combination of both, packet routing and facility-layer forwarding, could be beneficial: Information of high importance could use the rapid, shot-like dissemination scheme at the network layer, while for information dissemination with less real-time requirements including the repetition of messages to keep them alive in a geographical area, a facility-layer forwarding scheme could be used. DENM, as standardized by ETSI, foresees such forwarding, but proposals for data aggregation and smart forwarding of DENM messages have not been made in a way that fits to the existing standards.

Congestion control mechanisms at facility layer appear equally important: [25] proposes a congestion control policy in which communication parameters are set based on a vehicle's application requirements opposed to system-level requirements, but still minimizes the channel load globally in the network. This appears to be an application-specific approach, whereas the FOT rather seeks for schemes that can be generally applied to at least a class of applications.

Management is commonly regarded as management of configuration parameters and for cross-layer information exchange. Many research efforts have addressed the cross-layer design of cooperative systems, which is a result of the modularization of protocols into layers and the need to dynamically exchange information among the layers. For this cross-layer information exchange, methods to distribute the information in a structured way stack has prevailed and efficient publish-subscribe-notification concepts for the asynchronous exchange of events are implemented (similar to the message dispatcher in [26]). There seem to be some uncertainty, which data are essential to exchange. As this question rather concerns which data are available for the generation of events and which ones are needed that are consumed on the other side, this appears rather as an engineering task of the individual layers.

Security. In order to analyze the vulnerability of cooperative systems, significant research has been carried out to identify assets, threats and potential attacks using different attacker models. Proposed security solutions cover several domains including cryptographic protection, ID management, privacy support, plausibility checks and in-vehicle security. The combination of all measures is supposed to provide a reasonably high protection level.

On the other side, the chosen security level has a number of system implications: The use of asymmetric cryptography results in a large protocol overhead due to the signatures and certificates appended to every message. Likewise, the need of a public key infrastructure (PKI) to distribute and revoke certificates creates an additional burden for the deployment and its operation diverges from the idea of a fully distributed ad hoc network. Finally, the high processing overhead for signature generation and verification and the need for real-time operations will likely require dedicated cryptographic hardware accelerators in vehicle and road-side units [27], which increases the unit costs compared with software-based solutions.

Despite the efforts on vulnerability analysis, there seem to be no consensus on which protocol layer the cryptographic protection should be applied. Network-layer signatures would secure the packet headers of the ad hoc routing protocol and may even protect multi-hop communication by hop-by-hop signatures additionally to end-to-end signatures. Alternatively, the protection of messages at the facility layer allows for direct usage of the IEEE 1609.2 standard for the European system.

For privacy support, the use of changing pseudonyms has been proposed and applied in FOTs. Clearly, a trade-off between the frequency of pseudonym change and proper functioning of forwarding algorithms based on network addresses exist, however a clear pseudonym change strategy is still not in practice. Plausibility checks have been suggested my various research as a measure to verify the consistency of received data. This can be achieved by comparing received data with other local sensor information, but also by cross-validation of data received from different sources. A valid approach is to assign a confidence value to every received information element, whereas this value increases the more the information is validated by other information.

The set of security solutions represents the state-of-the-art that is considered in the FOT, though only relevant parts are implemented. The imposed overhead and the considerable efforts to set up and operate the system have triggered researchers to study alternatives. One approach is the use of symmetric cryptography or group signatures as an alternative to the currently considered asymmetric scheme. Furthermore, alternative ad hoc routing schemes, such as cluster-based routing, may allow to create trust between ad hoc nodes. However, those alternatives tend to deeply affect the overall system design and are not considered in an FOT.

4. CONCLUSIONS

Currently, field operational tests for impact assessment of cooperative systems are carried out. In Europe, the cooperative system technology used in FOTs, such as the DRIVE C2X project, relies on a solid basis that has been consolidated over the past years. A first series of ETSI standard for cooperative systems has been completed; it covers core technology components such as IEEE 802.11p PHY&MAC, GeoNetworking, facilities (CAM, DENM), IEEE 1609.2 security and others. Once standardization is completed and product development finalized, a simple yet robust system is ready to be introduced and effectively deployed. At the same time, this minimal system bears various opportunities for improvements and we have elaborated a selection of research proposals for access technologies, networking and transport, middleware as well as management and security. At the stage of impact assessment of the technologies by field tests it appears rather unrealistic to bring new communication paradigms for cooperative system into the real world. Nevertheless, all layers of the protocol stack and algorithms deserve extensions and improvements.

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