A Highly Scalable IEEE802.11p Subsystem Using Communication and Localization for Increased Vehicular Safety

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***Abstract*—The IEEE802.11p standard describes a protocol for car-to-X and mainly for car-to-car-communication. It has found its place in hardware and firmware implementations and is currently tested in various field tests. In the research project Ko-TAG, which is part of the research initiative Ko-FAS, cooperative sensor technology is developed and its benefit for traffic safety applications is evaluated. A secondary radar principle based on communication signals enables localization of objects with simultaneous data transmission. It mainly concentrates on the detection of pedestrians and other vulnerable road users (VRU), but also supports pre crash safety applications.**

The Ko-TAG proposal enriches the current IEEE802.11p real-time characteristics needed for precise time-of-flight real-time localization. This contribution describes the development of a subsystem, which extends the functionality of IEEE802.11p and fits into the regulatory schemes. It discusses the approach for definition and verification of the protocol design, while maintaining the close coexistence with existing IEEE802.11p subsystems. System simulations were performed and hardware was implemented. The next step will be field measurements to verify the simulation results.

***Index Terms*—IEEE802.11p/WAVE, subsystem design, VRU eSafety, localization, secondary surveillance radar, standardization**

I. Introduction

The IEEE802.11p standard has developed as the most popular basis for C2X-communication [1]. For the USA, the “IEEE 1609 Family of Standards for Wireless Access in Vehicular Environment (WAVE)” [2] defines an architecture and a complementary, standardized set of services and interfaces that collectively enable secure car-to-car (C2C) and car-to-infrastructure (C2I) wireless communications. IEEE802.11p will be used as the platform for Dedicated Short Range Communications (DSRC), a U.S. Department of Transportation (DoT) project based on the ISO Communications, Air-interface, Long and Medium range (CALM) architecture standard looking at vehicle-based communication networks, particularly for applications such as toll collection, vehicle safety services, and commerce transactions via cars.

The European activities are also based on IEEE802.11p Wireless LAN. A frequency spectrum in the 5.9 GHz range has been allocated on a harmonized basis in Europe [3] in line with similar allocations in USA. Here the higher layers are defined by the Car2Car Communication Consortium [4]. Car2X communication technology enables a number of new use cases in order to improve driving safety or traffic efficiency and provides information or entertainment to the driver [2]. IEEE802.11p has found its place in hardware and firmware implementations, and is currently extensively tested in various large-scale field tests, i.e. in the German simTD test field [5].

In parallel to the need for information exchange between cars, an important trend has evolved during the last years. This trend is based on the fact that during the significant reduction of absolute numbers of accidents and fatalities in traffic (at least in Europe), the relative risk for vulnerable road users (VRUs), i.e. for pedestrians, cyclists, powered two wheelers, etc., has significantly increased [6].

In general, precise perception of the vehicle’s environment is an essential requirement for all preventive vehicle safety systems. For example, today’s advanced driver assistance systems (ADAS) are based on on-board environment perception sensors. It is only shortly that ADAS also offers predictive pedestrian protection systems (PPPS) functionality. These predictive systems use contact- or non-cooperative perception sensor systems for the detection of a pedestrian in the vicinity. They are limited by uncertainties in target classification. Moreover, these systems offer no benefit in case of fully or partially hidden pedestrians like e.g. children hidden by cars parked at the roadside. Cooperative pedestrian protection systems (CPPS) that follow the

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communication model of secondary surveillance radar from air traffic control overcome these weaknesses. Cooperative systems may be used alone or in conjunction with image-based systems, like e.g. [7], [8]. The technology can also be used for an omnidirectional perception system for pre-crash safety and as sensor support for intersection safety.

The remainder of this paper is organized as follows: Due to its limitations in scalability and real-time location capability, the IEEE802.11p/WAVE-protocol approach is not ideally suited for these kinds of applications, which will be discussed in ch. II.

Therefore, within the research project Ko-TAG, which is part of the research initiative Ko-FAS [9], a solution has been proposed, which enriches the current IEEE802.11p protocols, enables it for additional application scenarios, and has been designed to work as an add-on subsystem, which may be seamlessly integrated into IEEE802.11p-based car-to-X-communication. The proposed subsystem protocol combines communication and localization. It was verified in simulation and is currently implemented and tested in custom hardware. It is presented more detail in ch. III. In the second half of the Ko-TAG project, it is an explicit objective to explore and pave the way for an international standardization of this approach. The arguments are presented in ch. IV.

II. IEEE802.11P/WAVE AND ITS RESTRICTIONS

A. Description

The IEEE802.11p amendment has developed as the most popular basis for C2X-communication [1]. The IEEE802.11p amendment can be understood as a refinement of the IEEE802.11a/h standards, which are the consumer WLAN solutions in the 5 GHz-bands.

On the PHY layer, IEEE802.11p usually uses the half clocked mode with 10 MHz bandwidth. Thus, the symbol length is doubled in comparison to IEEE802.11a/h, making the signal more robust against fading. In addition, the IEEE802.11p signal uses a carrier spacing reduced by ½ compared to IEEE802.11a/h. Beside the clock rate, the adjacent channel rejection in IEEE802.11p is more stringent than in IEEE802.11a/h, as is the spectrum emission mask.

On the media access control (MAC) layer, a new management information base (MIB) “dot11ocb” is defined into the MAC Layer Management Entity (MLME). When “dot11ocbenabled” is true, additional options/constraints are added to an IEEE802.11p device. The additional options are [10]:

a) no authentication service, which would be provided by the station management entity (SME) or by applications outside of the MAC sublayer,

b) no deauthentification service, and

c) data confidentiality. Additionally all stations belong a priori to one pre-defined “C2C” Independent Basic Service Set (IBSS).

B. Characteristics & Requirements

The changes of IEEE802.11p in comparison with IEEE802.11a are oriented towards only minor aspects, as described in subsection A. However, the requirements of the target application are very disjunctive to the capabilities of both IEEE802.11a and p. I.e. three requirements are critical. They are described in the following three subsections.

C. Real-Time Characteristics

Analyses of accidents show that the precise localization deadline is at a distance of around 50 m under the assumption of intra-urban vehicle speeds of 50 km/h. This deadline leads to the range requirement of around 75 – 100m for communication setup and first measurements.

It should be highlighted that this range should be achievable not only under free-space conditions, but in real environments, additionally taking into account multi-path propagation, attenuation by cars, human bodies, building, and other obstacles, diffusion, and refraction.

Thus, reaction times in the pre-crash scenarios are very short and in the range of 500 ms to 100 ms, and must be subject by a very low jitter, especially in critical use cases. These times shall include several measurements and information exchanges. Theoretical analyses and practical experience show that these times cannot be achieved in multi-user scenarios (c.f. subsection D).

D. Density and Scalability

The density of vehicles may be high, however is limited through the dimensions of a car. Consequently, for car2car-communication, a maximum density of 1 node per 20 m^2 (traffic jam) or per 60m^2 (city traffic) is typically anticipated. VRU nodes may be much denser. This especially holds true for intra-urban situations at intersections, where waiting pedestrians may reach a density of 2 to 3 nodes per m^2.

The required range of (for example 75 m) leads to a maximum area of Pi*(75 m)^2= 17,662 m^2, which together with the anticipated density leads to a maximum number of up to 50.000 VRU nodes within the vicinity of one vehicle node. In addition, further vehicles will also be active in the neighborhood. Of course, one might argue that no-one would crash incidentally into a crowd of 50.000 people. Nevertheless, the stability of the anticipated system shall be fulfilled also in such use-cases.

The characteristics of IEEE802.11p are oriented to much smaller densities and maximum network sizes of some dozens of nodes.

E. Localization

No support for localization apart from simple signal-strength-(RSSI)-based approaches is foreseen in IEEE802.11p. These approaches achieve accuracies of several meters or even tens of meters in dynamic environments without the possibility of training [11].

Therefore, additional features shall support time-of-flight-(ToF) and direction-of-arrival-(DoA)-measurements as integrated elements.

III. The Proposed Subsystem

A. Overall Approach

As a consequence of the given situation and the requirements of the target application described above, the proposed subsystem follows a dual approach:

- It shall use as many elements from IEEE802.11p as possible, so that the new functionality can be implemented as a subsystem and can be seamlessly integrated into IEEE802.11p hardware.
- It shall implement additional features to support the given requirements. Those shall be as close as possible to the given characteristics. The additional features include functionality, such as localization, but also improved network characteristics, such as scalability or real-time behavior.

B. System Description

Within the Ko-TAG-architecture, it is anticipated that vehicles are equipped with a Localization Unit (LU), which communicates with SafeTAGs (ST). Such a ST can be given to any secondary partner. In its original purpose, a VRU is equipped with a ST. In addition, if the ST is given to another vehicle, a significant extension of the project scope with regard to omnidirectional safety will be achieved. The integration of infrastructure, i.e. at intersections, could further improve the functionality and the accuracy of the system. This intersection use case is currently addressed in a neighbor project (Ko-PER) and can eventually be extended by the Ko-TAG communication and localization. Fig. 1 shows the potential links between traffic objects.

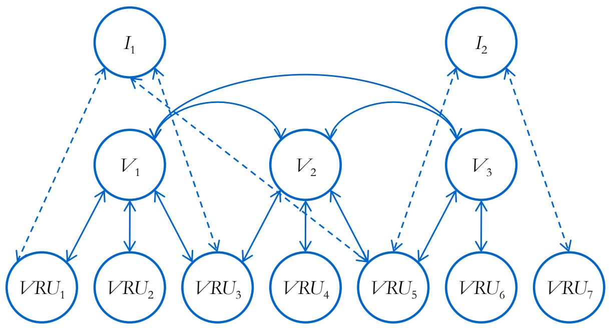

Figure 1. Supported topologies within the Ko-TAG project; Dotted lines show the potential additional links within the overall Ko-FAS approach

The communication is organized in super frames, in which communication and localization between various pairs are organized. The channel access divides into three phases, which can be multiplexed in various dimensions, i.e. time and frequency (cf. Fig. 4):

- A detection and network management phase, when VRU tags can register to vehicles.
- A time of flight (ToF) measurement phase, which is extremely time critical, as clock drifts between measurement partners lead to localization errors.
- A direction of arrival (DoA) measurement phase, which can be used in parallel for data communication.

Thus, the channel access combines contention periods for arbitrary and management traffic, and contention free periods (reserved time slots) for time- and collision-critical operations. The physical breakup into the different frequencies helps to solve the conflict of objectives with regard to bandwidth requirements.

- According to radar theory, the resolution and hence the accuracy of ToF-distance measurements grows with the use of increasing RF bandwidth. Therefore, it is highly preferable to use a channel with maximum frequency bandwidth. Since the maximum bandwidth of the available IEEE802.11p channels (cf. Table I) is limited to 30MHz, a frequency range outside of the IEEE802.11p band from 5775MHz to 5825MHz was chosen as a first step. Ongoing research activities try to minimize the bandwidth requirements of the ToF subsystem so integration into the standard 802.11p bands might be an option in the future, too.
- On the other hand, the precision of DoA measurements is best with minimum bandwidth. Here the possibility to extract single carriers from the IEEE802.11p OFDM PHY gives the benefit to have a narrow-band signal for the DoA measurement without losing bandwidth for the simultaneous data communication. Currently the IEEE802.11p channel no. 5 (cf. Table I) is used for the DoA measurements and data transmissions.
- The exchange of control information is done in channel no. 9 (c.f. Table I) that has the same characteristics as the DoA/Data channel. This holds up the possibility to use control information packets for additional DoA measurements in future implementations of the protocol.

The system shall be flexible enough to support further functionalities, like pre-crash safety, or safety of intersections. Both aspects are also explored within the Ko-FAS initiative.

C. Validation

In parallel with the design of the protocol, a simulation environment has been prepared in order to verify the macroscopic soundness of the chosen concept and its interoperability with existing systems. OPNET models have been designed and extensively simulated [12]. Fig. 5 shows one of the resulting diagrams.

D. System Implementation

After the design and the verification of the protocol, the custom hardware has been developed and produced.

The cooperative sensor system developed in the Ko-TAG project consists of On-Board units (OBU) and transponders called SafeTAGs (ST). The sensor concept allows for a selective localization of STs and a selective communication link between localization units and STs for an efficient use of the available bandwidth (link (2) in

Fig. 2). Furthermore there is a lightly modified version of the ST that can be connected to an OBU via a TCP/IP link to provide omnidirectional safety amongst vehicles (link (3) in Fig. 2).

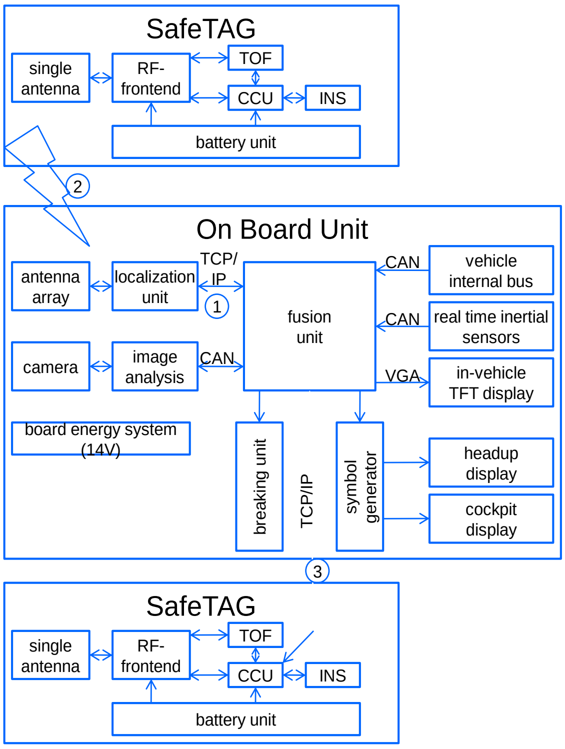

Figure 2. Block diagram of the Ko-TAG communication and measurement elements

The hardware design includes the complete system design from RF-frontend over signal processing, network operation until Gigabit-Ethernet-interfacing to the vehicle's On-Board Unit (OBU). Fig. 3 shows the prototype boards being developed in the Ko-TAG project. At the time of submission, the boards are taken into operation. Results from field measurements will be available in the upcoming year 2013.

Figure 3. Prototype Hardware for Ko-TAG demonstrators integrating the ToF- and AoA-measurement units, the baseband processing, the networking management and a Gigabit-Ethernet-Interface

IV. Discussion of Upcoming Standardization

A. *Objectives of Standardization Efforts*

The following aspects are the essential arguments for the efforts towards standardization:

- Multi-Vendor Interoperability: The anticipated application cannot be thought without support of multi-vendor interoperability. Parallel, non-interoperable systems would impede market penetration. If multi-protocol solutions would become necessary, this would increase system cost, size, and energy consumption at both car manufacturers and other road users.
  Besides, it is clear, that the same rules for the sub-systems as for the main C2C-systems exist.
- Openness: It also seems attractive to open the standard to the community, as for the market penetration, two aspects are of essential importance. With regard to VRU safety, the VRU tag is expected to be a consumer product, with a completely different product design and marketing approach, than that of car manufacturers, be it OEM, 1st tier or others, but it might be manufacturers of schoolbags, e-bicycles, or even smart-phones. With regard to the car side, a continually increasing endurance of cars and thus a growing average car age on roads can be observed. Therefore, it can be expected that retrofit products will be an important element for the market success.
- Regionalization: From a regulatory standpoint, it is likely that not all world regions will agree on a common frequency band allocation (cf. subsection C). Therefore, it must be envisaged that there might be some minor adaptations in the actual use of frequencies. Comparable to the upcoming C2C-communication, it should be a major approach to have those characteristics close enough for unified hardware solutions.

B. *Industrial Basis and Involved Partners*

An important element of the presented research project is the participation not only of academic institutions, but also the direct and strong involvement and commitment of major industrial partners, like OEM, 1st tier manufacturers, but also sensor vendors [13]. As the presented project is funded from German government, the list currently includes German manufacturers. However, neighbor projects on the European level, like WATCH-OVER [7], have already shown the European vision. Further international projects are envisaged for the future.

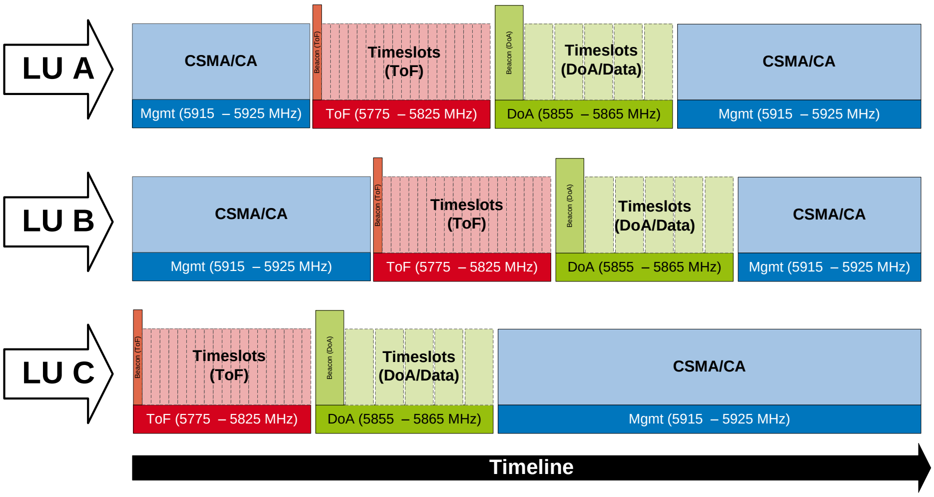

Figure 4. Time-and frequency multiplexing in the proposed Multi-Channel Splitted Localization (MCSL) approach

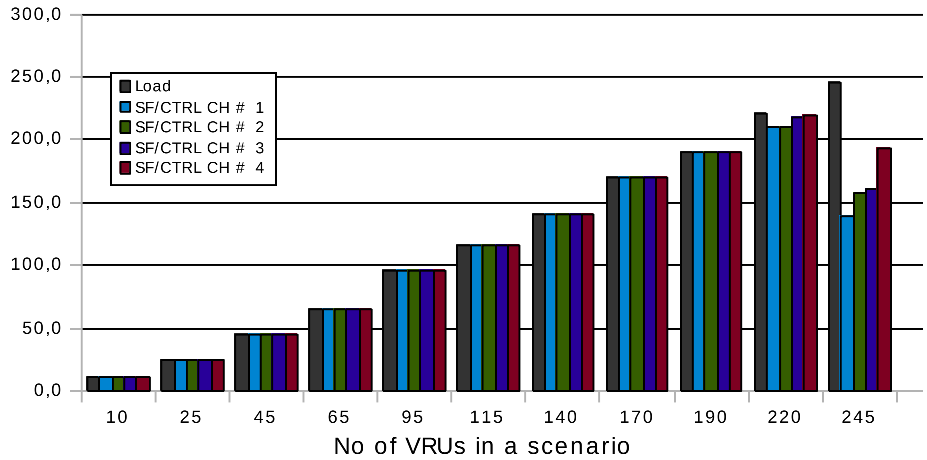

Figure 5. Number of Connected VRUs in dependence of the Number of VRUs in the scenario and the number of control channels per super frame considering 75 TOF slots per superframe

C. *Regulatory Issues*

ETSI as European regulatory body has opened ten channels in the 70 MHz broad frequency range between 5.855 and 5.925 GHz in ETSI EN 302 571 [3]. This allocation is listed in Table I. It should be highlighted that the seven 10 MHz-channels are non-overlapping and can be used independently. Alternatively, the bandwidth can be split into two 20 MHz and one 30 MHz channel. IEEE802.11p uses these channels with an OFDM PHY.

V. Outlook and Further Activities

In the remaining year of the Ko-TAG project, extensive measurement campaigns will be performed in order to prove the results from simulation. In addition, it is an explicit objective to explore and pave the way of standardization of the approach, through dissemination, preparation of subsequent projects, and discussion with standardization bodies.

TABLE I. Available Channels in the 5.9 GHz Band as Defined by ETSI EN 203 571 [3]

Channel number	Carrier centre frequency [MHz]	Maximum channel bandwidth [MHz]
1	5860	10 (5855-5865)
2	5865	20 (5855-5875)
3	5870	10 (5865-5875)
4	5880	10 (5875-5885)
5	5890	10 (5885-5895)
6	5900	10 (5895-5905)
7	5910	10 (5905-5915)
8	5915	20 (5905-5925)
9	5920	10 (5915-5925)
10	5890	30 (5875-5905)

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