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Communication-Based Intersection Safety: Motivation, Challenges and State-of-the-Art

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***Abstract*—**
V2X communication has recently attained significant attention from both academia and industry because it has the potential to improve road safety and to reduce road accidents and fatalities. For this reason, V2X communication has been considered an important part of future *Intelligent Transportation Systems* (ITS). In V2X communication, vehicles are equipped with IEEE 802.11-based wireless network interfaces and can spontaneously form an ad hoc network among themselves. Vehicles can use this ad hoc network to communicate with each other in order to support safety applications such as cooperative collision warning.

Several R&D projects around the world have been investigating various aspects of V2X communication. Some of these projects focus on specific issues of V2X communication for intersection safety because intersections are the most complex driving environments and include not only vehicles but also other road users such as pedestrians and cyclists. Thus, distraction or unpredictable behavior of a single driver can have a grave impact on many other road users. For this reason, intersection accidents occur frequently. Further, these accidents are usually very serious and usually involve several users. In this paper, we first review use cases for communication-based intersection safety. We then derive the requirements from these use cases and discuss their challenges. Based on these requirements, we present a protocol architecture for communication-based intersection safety that fits into the overall architecture of V2X communication.

I. Introduction and Motivation

Recent years have witnessed a significant growth in the area of information and communication technologies (ICT). In order to facilitate the incorporation of ICT into on-board intelligent vehicle systems and transportation infrastructure, the European Commission has recently started the *Intelligent Car Initiative* [1]. Intersection safety is one of the challenges in the *Intelligent Car Initiative* because accidents at intersections account for approximately 50% of all injury accidents. For this reason, intersection assistance is highly desired for improvement of intersection safety. Within this context, communication-based intersection assistance has the potential to reduce the number of accidents considerably.

Intersections are complex driving environments and involve not only cars but also other road users such as pedestrians and cyclists. It is difficult for drivers to detect all other road users and to predict their movements accurately. An *Intersection Assistant* equipped with communication technologies combined with different sensors can alleviate this difficulty by detecting potential accidents and providing drivers with warning messages, for example in left-turn scenarios. Moreover, communication technologies at intersections enable various applications for traffic efficiency (such as speed recommendations and announcements of switching times from traffic light).

Significant research activities for intersection safety have been conducted in different projects [2], [3], [4], [5]. However, many questions related to vehicle-to-vehicle and vehicle-to-infrastructure communication (abbreviated as V2X communication) for intersection safety remain open. For example, previous work implemented proprietary solutions for V2X communication as a proof of concept but did not consider important standards currently being defined in the Car-to-Car Communication Consortium (C2C-CC) [6] and the ETSI Technical Committee for Intelligent Transport Systems (ETSI TC ITS). Further, V2X communication solutions developed so far do not consider multi-hop forwarding, a networking technology that can provide important benefits for road safety by significantly extending a driver's vision and increasing his reaction time.

In this paper, we investigate V2X communication for intersection safety in a top-down approach by first identifying its challenges and requirements. Our approach is is illustrated in Figure 1 and is divided into three main steps. First, we systematically analyze the applications and use cases for communication-based intersection assistance for safety and traffic efficiency. Second, we derive requirements and identify challenges for these use cases. Third, we present our protocol architecture for communication-based intersection safety that seeks to address these challenges.

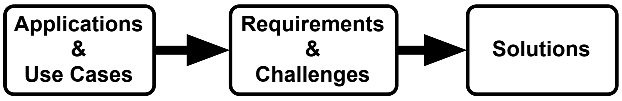

Fig. 1. Analyzing the State-of-the-Art of Intersection Assistance

II. Background and Related Work

Thanks to its importance, intersection safety has been investigated in several research projects around the world. In this section, we review a number of important activities for intersection safety in Europe, Japan, and the U.S. We pay special attention to communication-based intersection safety.

A. Communication-Based Intersection Safety in Europe

In Europe, specific issues related to V2X communication at intersections were first addressed in the pioneering project INTERSAFE which combined sensor and communication technologies to increase intersection safety [2], [7], [8]. INTERSAFE's goal was to develop an *Intersection Assistant* that can reduce or even eliminate fatal accidents at intersections. An *Intersection Assistant* can provide intersection safety in two main ways. First, the *Intersection Assistant* can help a vehicle detect others in its neighborhood by means of sensors and bidirectional wireless communication based on the IEEE 802.11 standard. When a potential collision is detected, a driver can be warned to stop for traffic from other directions. Second, a traffic light controller can also be equipped with sensors and communication devices. In this way, the traffic light controller communicates with approaching vehicles via bidirectional wireless communication and informs them about the traffic light's status, road conditions and potential hazards detected by sensors installed at an intersection.

B. Communication-Based Intersection Safety in Japan

In Japan, the Driving Safety Support Systems (DSSS) have been investigated by the National Policy Agency and the Universal Traffic Management Society of Japan (UTMS) [5], [9]. DSSS strives to prevent accidents by providing drivers with warning about potential danger at intersections. Main target scenarios for DSSS are stop sign violation, red light violation, turning accidents, crossing-path accidents, rear-end collision, and collision with pedestrians. For DSSS, UTMS has been developing vehicle-infrastructure cooperative systems and conducting operational tests in four different test sites: Tochigi, Aichi, Kanagawa, and Hiroshima [4], [10].

The roadside infrastructure of DSSS consists of an infrared beacon and a Dedicated Short Range Communication (DSRC) beacon. The infrared beacon is placed before an intersection while the DSRC beacon is installed near an intersection. The infrared beacon is periodically broadcast by the roadside infrastructure and realizes two main functions. First, it delivers static information such as road alignment, distance to the intersection, and traffic regulation. Second, it informs approaching vehicles about their specific geographic location and their lane number (infrared beacon is particularly suited for this purpose since its communication range is limited within a few meters and thus provides good accuracy for localization). The DSRC beacon is broadcast periodically and provides dynamic information at an intersection such as position and speed of pedestrians or other vehicles as detected by roadside sensors. DSRC beacon can provide relevant messages for specific lanes at an intersection. In this case, a vehicle's onboard unit (OBU) can perform message filtering using the vehicle's lane number as provided by the infrared beacon. The OBU performs a risk analysis based on information received from the roadside infrastructure. If imminent danger is detected, OBU delivers an acoustic or a visual warning signal.

Initial system evaluation for DSSS has been conducted and received positive feedback from test subjects. The evaluation also demonstrated that considerable speed reduction could be achieved for vehicles approaching an intersection. Further cooperative experiments between DSSS and Advanced Safety Vehicle (ASV) are currently being considered for future large-scale ITS operational tests.

C. Communication-Based Intersection Safety in the U.S.

Intersection safety is addressed in the Cooperative Intersection Collision Avoidance Systems Initiative (CICAS) in the U.S. [3], [11]. CICAS implements critical safety applications combining different ITS technologies to reduce intersection accidents by providing real-time warnings both in the vehicle and on the infrastructure. The ITS technologies used in CICAS include in-vehicle positioning, roadside sensors, intersection maps, and two-way wireless communication. For wireless communication, CICAS leverages the DSRC technology developed in the Vehicle Infrastructure Integration program (VII). Four main safety applications are developed in CICAS.

CICAS-Violation Warning System (CICAS-V). This application allows the infrastructure to send status information of the traffic light to approaching vehicles using DSRC. Based on this information and in-vehicle GPS, CICAS-V estimates the risk that the vehicle will violate a traffic light. If this risk is sufficiently high, CICAS-V provides a warning to the driver. Two important objects contained in CICAS-V messages are SPAT (signal phase and timing) and GID (geometric intersection description). SPAT informs an approaching vehicle about the traffic light's status and its remaining time. GID provides geospatial encoding and reference points of an intersection.

CICAS-Stop Sign Assist (CICAS-SSA). This application uses sensors installed at an intersection to help drivers in deciding when they can proceed onto or across a high-speed road after stopping at a rural road stop sign. CICAS-SSA provides drivers with assistance either via animated display sign or wireless communication.

CICAS-Signalized Left-Turn Assist (CICAS-SLTA). This application uses infrastructure sensors and wireless communication (building from CICAS-V) to assist drivers in making turning maneuvers at an intersection. The application takes oncoming traffic, pedestrians, and other obstacles into consideration.

CICAS-Traffic Signal Adaptation (CICAS-TSA). This application combines infrastructure sensors and wireless communication (building from CICAS-V) to detect a dangerous situation when a vehicle violates a red light and can potentially collide with other vehicles. In this case, CICAS-TSA triggers a red light in all directions to protect drivers from an imminent danger. Further, when a vehicle detects a dangerous situation, it can also send a warning message to the infrastructure to trigger an all-red traffic light and prevent a chain reaction of accidents.

D. Summary of Related Work

A number of pioneering projects in Europe, Japan, and the U.S. have addressed intersection safety. However, many questions related to V2X communication for intersection safety still remain open. While these projects laid the groundwork for V2X communication at intersections, they did not address several important issues of V2X communication such as robustness, reliability, and scalability. Further, these projects did not consider multi-hop forwarding, an important V2X networking technology that can provide significant benefits for road safety by extending a driver's vision and increasing his reaction time. We plan to address these issues in the ongoing EU project INTERSAFE-2 [12].

III. Applications and Use Cases

In this section, we discuss several use cases that can be supported by communication-based intersection safety. Some of these use cases have been identified by the pioneering projects reviewed in Section II. While the use cases discussed here are not meant to be comprehensive, we believe that they are representative for communication-based intersection safety.

Prevention of traffic light violation. In this use case, an infrastructure-based intersection assistant can use V2X communication to inform approaching vehicles about the traffic light's status and the remaining time until the status changes. Since a traffic light system is inherently complex and involves many inputs such as inductive loops and push buttons for pedestrians, traffic light can change somewhat unpredictably. For this reason, real-time V2X communication is necessary to provide vehicles with accurate and up-to-date signal phase of a traffic light. Given a traffic light's status, a vehicle can deliver a warning to a driver when a potential traffic light violation is detected. Further, the vehicle can also adjust its velocity to achieve optimized fuel consumption.

Prevention of turning and crossing-path collision. This use case assists drivers in their turning or crossing-path maneuvers at an intersection. Sensors installed at an intersection can detect objects and vehicles and construct an overview of the intersection. This view can be broadcast at a regular interval on the wireless channel to inform a driver about the presence of other road users at an intersection. Further, V2X communication can be used as an enabling technology for cooperative fusion of sensor data acquired in vehicles and at the infrastructure side. Cooperative data fusion provides a driver with a better vision of an intersection and helps detect other road users that the driver would overlook due to obstacles, distraction, or bad weather. Special protection for vulnerable road users (VRUs) can be obtained.

Prevention of rear-end collision. This use case prevents an accident from happening when a vehicle reduces its velocity abruptly at an intersection and other vehicles behind it do not have sufficient time to react. In this use case, multi-hop V2X communication can distribute a message within an intersection's surrounding area to warn other drivers. The warning message can be triggered by a vehicle's braking system or infrastructure-based sensors. Further, the traffic light controller can use V2X communication to inform drivers about the recommended driving speed before they enter an intersection. With this information, drivers can avoid reducing their speed abruptly at an intersection.

Traffic signal adaptation for emergency warning and prioritized road users. This use case can provide a dynamic traffic signal adaptation when an accident occurs at an intersection. In this case, an intersection assistant can broadcast an alert on the wireless communication channel. Further, in case a vehicle causes an accident, it can also send an emergency message to the infrastructure to trigger an all-red traffic light and prevent other vehicles from entering the intersection until the situation becomes clear. In emergency scenarios, an intersection can also support prioritized road users, e.g., emergency vehicles by giving them the green light in their direction.

Traffic efficiency. In this use case, RSUs can monitor road conditions and traffic density at intersections and provide a backend traffic management center with real-time information. Using this information, the traffic management center can obtain a global view of road systems and can compute alternate routes for vehicles. The traffic management center sends this information back to RSUs to inform the drivers. Drivers can use this information to optimize their route selection according to their needs.

IV. Requirements and Challenges

We summarize the challenges for V2X communication at intersections. These challenges serve as requirements for a protocol architecture for communication-based intersection safety that we derive in Section V.

Dynamic and distributed nature of VANETs. Before V2X communication can take place, cars must form a vehicular ad hoc network (VANET) in a distributed and self-organizing manner. Further, since cars can move at a high speed, a VANET can be highly dynamic. For this reason, fast and efficient mechanisms for bidirectional communication between cars and an *Intersection Assistant* are necessary. In particular, an *Intersection Assistant* should be compliant with V2X communication protocols currently being defined in important standardization bodies such as C2C-CC and ETSI TC ITS. Further, these protocols should operate in the protected frequency band specified by the governments (U.S., Europe, or Japan).

Channel congestion. Intersections can have a high vehicle density because only cars on certain lanes can move at any point in time while others have to stop. In particular, large intersections with multiple lanes in each direction can have very high vehicle density during rush hour. For example, the estimated number of cars at an intersection can be as high as 600 [13]. Since each car has to broadcast periodical beacons to inform others about its presence, the channel load can be very high. Due to the broadcast nature of the wireless medium, channel congestion can result in packet collisions. This situation is further aggravated because V2X communication relies on the standard IEEE 802.11p, a CSMA/CA wireless technology that is susceptible to the hidden node problem. Thus, efficient congestion control mechanisms for V2X communication are necessary at intersections.

Flexible and efficient communication architecture. An *Intersection Assistant* will rely on advanced sensor technologies such as radar sensors, laser scanners, and video cameras [2], [12]. Thus, it needs a flexible communication architecture that allows different subsystems to share information and commonly achieve safety for road users. Further, since sensor nodes can also form an ad hoc network among themselves, an *Intersection Assistant* also need to support a hybrid communication architecture to facilitate the incorporation of sensor communication [14].

Channel errors. Wireless communication are susceptible to errors due to channel noise and channel fading caused by multi-path propagation. Further, wireless signals can also be blocked by houses or buildings near intersections. Channel errors can be mitigated by installing an antenna of the *Intersection Assistant* at a location with a good view over the intersection. Further, multi-hop forwarding, an important networking technology currently under discussion in standardization bodies such as C2C-CC and ETSI TC ITS, allows nodes that cannot reach each other directly to communicate with each other.

V. Communication Architecture

We propose a protocol architecture for communication-based intersection safety that

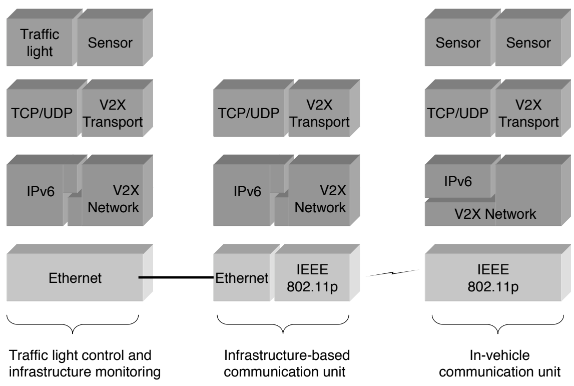

Fig. 2. Protocol architecture for communication-based intersection safety.

supports the use cases mentioned in Section III and addresses the challenges and requirements discussed in Section IV. Our protocol architecture is illustrated in Figure 2. On the infrastructure side, a communication unit installed at an intersection is equipped with a network interface card based on the IEEE 802.11p technology for wireless access in the vehicular environment (WAVE). This 802.11p-based network interface allows an intersection assistant to join the ad hoc network formed by the vehicles and communicate with them. The infrastructure-based communication unit also has an Ethernet interface that connects to the traffic light control and other infrastructure-based sensor systems (laser scanners and video cameras). The infrastructure-based communication unit serves as a gateway and relays data between the vehicles and the infrastructure side in order to support the use cases discussed in Section III. For this purpose, the V2X network and transport layer are used [15]. Legacy applications running TCP/IP are also supported. In this case, NEMO and IPv6 can run on top of the V2X network layer [16].

For illustration purpose, we depict only one in-vehicle communication unit in Figure 2. However, the intersection assistant can also communicate with vehicles that are not in its direct communication range. In this case, multi-hop communication take place and data packets are forwarded by the vehicles at the V2X network layer in a hop-by-hop manner.

VI. Summary

V2X communication has been considered a key ITS technology due to the fact that short-range wireless communication technology has become mature, inexpensive, and widely available. Using V2X communication, a vehicle can communicate with other vehicles in its vicinity in order to support safety applications such as cooperative collision warning. For intersection safety, V2X communication can be used as an enabling technology to combine traffic light system, in-vehicle sensors, and infrastructure-based sensors. In this paper, we review state-of-the-art of communication-based intersections safety and highlight several use cases. We derive the requirements and identify the challenges of intersections safety. Based on these requirements, we present a protocol architecture for communication-based intersection safety.

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