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V2X Communication and Intersection Safety

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Abstract

Vehicle-to-vehicle and vehicle-to-infrastructure communication (V2X communication) has great potential to increase road and passenger safety, and has been considered an important part of future Intelligent Transportation Systems (ITS). 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 (communication-based intersection safety) because intersections are the most complex driving environments where injury and fatal accidents occur frequently. In this paper, we discuss the technical details of V2X communication and discuss how it can be used to improve intersection safety.

1 Introduction

In recent years, V2X communication has attained significant attention from both academia and industry because it has great potential to increase road and passenger safety. Several R&D projects around the world have been working on different aspects of V2X communication. Some of these projects have been investigating specific issues of V2X communication for intersection safety (communication-based intersection safety) because intersections are the most complex driving environments where injury and fatal accidents occur frequently. Research activities for communication-based intersection safety have been conducted in different research projects in Europe, Japan, and in the U.S. [1, 2, 3, 4]. However, many questions related to communication-based for intersection safety remain open. For example, previous work implemented proprietary solutions for communication-based intersection safety as a proof of concept but did not consider important standards currently being defined in the Car-to-Car Communication Consortium (C2C-CC) [5] and the ETSI Technical Committee for Intelligent Transport Systems (ETSI TC ITS). Further, solutions for communication-based intersection safety 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 an integrated approach for communication-based intersection safety by considering it in the big picture of V2X communication. The rest of our paper is organized as follows. We review relevant related work in Section 2. We provide the background for V2X communication in Section 3. We discuss how V2X communication can improve intersection safety in Section 4. We summarize our paper in Section 5.

2 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.

2.1 Communication-Based Intersection Safety in Europe

In Europe, specific issues related to communication-based intersection safety were first addressed in the pioneering project INTERSAFE which combined sensor and communication technologies to increase intersection safety [1, 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 802.11p 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.

2.2 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) [4, 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 [3, 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.

2.3 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. [2,11]. 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.

2.4 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 communication-based intersection safety still remain open. While these projects laid the groundwork for communication-based intersection safety, 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 [6].

3. V2X Communication

The core networking concept for V2X Communication is *Geocast*, an ad hoc routing protocol that provides wireless multi-hop communication over short-range wireless radio without the need of a coordinating infrastructure as in cellular networks. The basic idea of *Geocast* was originally proposed for mobile ad hoc networks [12] and has been further developed for other systems, i.e., wireless sensor networks and vehicular ad hoc networks.

In principle, *Geocast* provides data dissemination in ad hoc networks by using geographical positions of nodes. For multi-hop communication, nodes forward data packets on behalf of each other. *Geocast* is attractive in vehicular environments for two reasons. First, it works well in highly mobile network where network topology changes frequently. Second, *Geocast* offers flexible support for heterogeneous application requirements, including applications for road safety, traffic efficiency and infotainment. In particular, *Geocast* provides periodic transmission of safety status messages at high rate, rapid multi-hop dissemination of packets in geographical regions for emergency warnings, and unicast packet transport.

Geocast provides two basic and strongly coupled functions: *geographical addressing* and *geographical forwarding*. With *geographical addressing*, *Geocast* can address a node by a position or address multiple nodes in a geographical region (*geo-address*). For *geographical forwarding*, *Geocast* assumes that every node has a partial view of the network topology in its neighborhood and that every packet carries a *geo-address*, i.e., the geographical position or geographical area as the destination. When a node receives a data packet, it uses the *geo-address* in the data packet and its own view of the network topology to make an autonomous forwarding decision. Thus, packets are forwarded "on the fly" and nodes do not need to set up and maintain routes. In order to achieve this, *Geocast* assumes that every network node knows its geographical position, e.g. by GPS or another positioning systems, and maintains a location table of geographical positions of other nodes as soft state.

Geocast has three core protocol components: *beaconing*, *location service* and *forwarding*.

- *Beacons*, also referred to as *heartbeats*, are small packets that each node broadcasts periodically to inform other nodes about its ID, its speed, its heading, and its current geographical position.
- Nodes can cooperatively provide *location service* that resolves a node's ID to its current position on a query/reply basis.
- *Forwarding* basically means relaying a packet towards the destination.

These three protocol components are combined to support *Geocast* forwarding. There are four types of *Geocast* forwarding: *Geographical Unicast (GeoUnicast), Geographical Broadcast* (*GeoBroadcast*), *GeoAnycast,* and *Topologically-Scoped Broadcast* (*TSB*).

- *Geographical Unicast (GeoUnicast)* (illustrated in Fig. 2) offers packet relay between two nodes via one or multiple wireless hops. When a node wants to send a unicast packet, it first determines the destination position (by means of location table look-up or the location service) and forwards the data packet to the next node in the direction of the destination. This node in turn re-forwards the packet along the path until the packet reaches the destination. Greedy forwarding is an algorithm for where a node selects the next hop based on position information such that the packet is forwarded in the geographical direction of the destination. An illustration of greedy forwarding is provided in Fig. 1.
- *Geographical Broadcast* (*GeoBroadcast*) (illustrated in Fig. 3) distributes data packets by flooding, where nodes re-broadcast a packet if they are located in the geographical region specified by the packet. Packet is forwarded only once: If a node receives a duplicate packet that it has already received, it will drop packet.

▶ *GeoAnycast* is similar to *GeoBroadcast* but addresses any node in a geographical area.

▶ *Topologically-Scoped Broadcast* (*TSB*) (illustrated in Fig. 4) offers re-broadcasting of a data packet from a source to all nodes that can be reached in certain number of hops (all nodes in an n-hop neighborhood). Single-hop broadcast is a special case of TSB that is used to send *heartbeats* including application data payload.

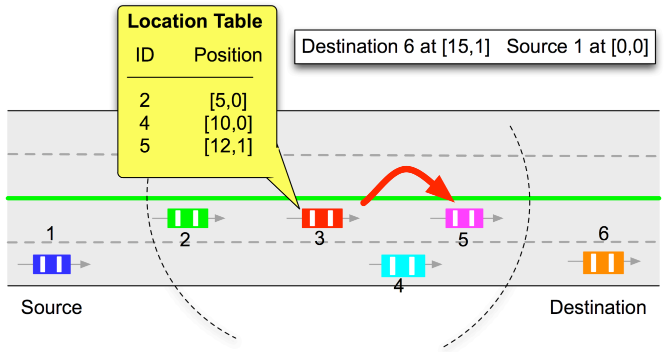

Fig. 1. Illustration of greedy forwarding: Node 3 selects node 5 as the next hop.

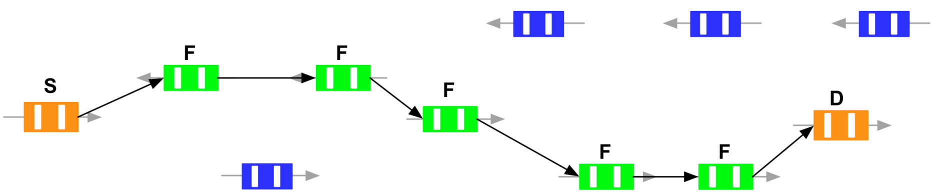

Fig. 2. Illustration of GeoUnicast.

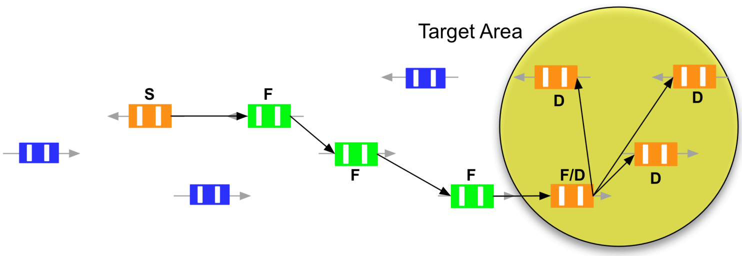

Fig. 3. Illustration of GeoBroadcast.

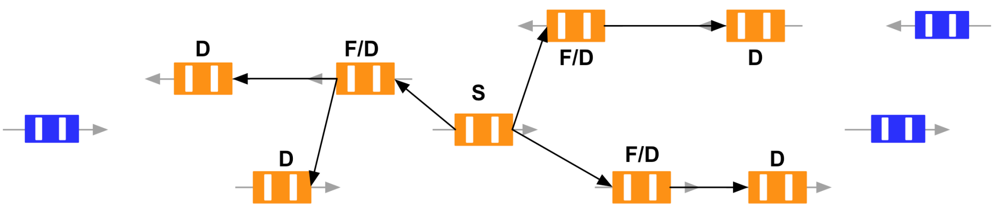

Fig. 4. Illustration of Topologically-Scoped Broadcast

In *Geocast*, a node usually processes all data packets that it receives on the wireless links to keep track of all nodes in its surrounding (this requires nodes to operate their network interfaces in promiscuous mode). Since each data packet contains the source's and previous forwarder's positions, a receiving node can update its location table accordingly. A *Geocast* packet header contains fields for node identifier, position and timestamp for source, sender, and destination, and more. The originator of a packet is referred to as source, and the last forwarder as sender. Fields in a *Geocast* header are classified as immutable and mutable: *Immutable fields* are not changed in the forwarding process. On the other hand, *mutable fields* are updated by forwarders. This allows a forwarder to change some header fields on the fly, e.g. in case it has more recent information in its location table about a given destination.

4. Applications and Use Cases

In this section, we discuss several use cases for communication-based intersection safety that can be supported by V2X communication. Some of these use cases have been identified by the pioneering projects reviewed in Section 2. 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 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. This use case can be supported efficiently by *GeoBroadcast* or *Topologically-Scoped Broadcast* forwarding.

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. This use case can be supported efficiently by *GeoBroadcast* or *Topologically-Scoped Broadcast* forwarding.

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. This use case can be supported efficiently by *GeoBroadcast* or *Topologically-Scoped Broadcast* forwarding.

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. This use case can be supported efficiently by *GeoBroadcast* or *Topologically-Scoped Broadcast* forwarding.

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. This use case can be supported efficiently by *GeoBroadcast* or *Topologically-Scoped Broadcast* forwarding.

We note that while *GeoBroadcast* or *Topologically-Scoped Broadcast* forwarding provide efficient support for most use cases, *GeoUnicast* and *GeoAnycast* forwarding might be useful for future use cases of communication-based intersection safety that are currently not considered.

5. 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 neighborhood 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 provide technical background for V2X communication. We review state-of-the-art of communication-based intersection safety and highlight several use cases where V2X communication can provide considerable benefits for intersection safety. We plan to address these use cases and open issues related to communication-based intersection safety in the ongoing EU project INTERSAFE-2 [6].

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