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Indirect Spatiotemporal Short-Range Vehicle Communication Approach Inspired on Capillary Waves

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Abstract. Short-range communication protocols allow for vehicles to exchange messages with the aim to provide new services for road security, emergency and intelligent transportation systems. For these services, each message has particular importance depending on where and when the event has happened. The message's importance degrades as time elapses and distance between the source and recipient increases. The similar effect can be observed on the water surface when an object falls on it. The resulting wave loses its strength with distance from the drop point and time. However, for vehicle communication, it is hard to establish this degradation due to: its distributed and asynchronous nature and the absence of permanent connections. This work presents an approach to establish the message's importance degradation while it is disseminated throughout a road network. To determine this effect, a fuzzy-causal closeness relation is used to combine information about traffic flow and location with temporal restrictions, expressed as causal dependencies. To face the lack of perdurable transmission links, the fixed communication elements embedded into the transportation infrastructure are used as communicant entities while vehicles are used as messages' carriers. In this way, the proposed solution operates with constant processing and communication overhead while the system scalability does not depend on the number of vehicles.

Keywords: spatiotemporal dependencies, fuzzy-causal closeness, capillary waves, indirect communication, short-range vehicle communication.

1 Introduction

Recent advances in wireless communication have allowed emerging standards for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, such as Dedicated Short-Range Communication (DSRC) [4]. This communication is mainly oriented to offer new services or enhance the current Intelligent Transportation Systems (ITS) such as lane change assistance, intersection coordination, emergency response time reduction, among others [7].

For these services, it is crucial to determine how important is a message depending on how far away and how long ago it was generated. For example, in an emergency response time reduction, traffic lights need to be coordinated to facilitate the circulation of emergency vehicles. In this scenario, an emergency vehicle dynamically adapts its trajectory according to the decisions of its driver and as a consequence, the nearest traffic lights must react to those changes.

As a message from the emergency vehicle is propagated through the road network, i.e. the farther it travels and the more time passes, the message loses its importance.

The same phenomenon can be observed on the water surface when an object falls. It produces ripples originating at the drop point of an object that propagates through the water surface. The resulting wave loses its strength with distance travelled and as time passes.

This scenario is depicted in Figure 1, where both the accident and the emergency vehicle generates capillary waves.

Even though this phenomenon is well studied by physics, it is hard to capture it in a V2V communication due to multiple factors. On the one hand, there are no perdurable transmission links among vehicles. On the other hand, interaction among vehicles is performed in a distributed and asynchronous fashion. As a result, it is hard to establish how far away and how long ago events have happened.

This work presents an approach for indirect spatiotemporal short-range vehicle communication inspired on capillary waves. To determine the messages' importance degradation, this approach is based on two main components: an indirect causal flooding protocol [3] and a fuzzy inference system to establish a degree of spatiotemporal closeness among events, that work together.

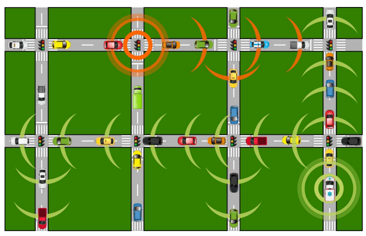

Fig. 1. Vehicular "capillary waves"

The causal flooding protocol was designed to face the lack of perdurable transmission links. However, this protocol establishes only the event order, but it cannot determine how long ago an event has happened.

This paper extends the flooding protocol by integrating a fuzzy inference system designed to support the constraints imposed by the asynchronous nature of interactions. In this sense, the spatiotemporal dependencies are estimated by combining heterogeneous data about traffic flow and location with temporal restrictions, expressed as causal dependencies.

By using these components, the solution does not require extra overhead. As a result, the system's scalability does not depend on the number of vehicles present in the system.

This paper is organized as follows. Section 2 presents a short overview of related works. The background and definitions are defined in section 3. The system model is presented in section 4. Section 5 describes the indirect spatiotemporal approach. The conclusions are presented in section 6.

2 Related Work

Several approaches have been proposed to determine whether the message in vehicular communication is important or not.

A Context-Aware Class Based Broadcast [2] proposes four different algorithms for message importance estimation. These algorithms consider one or two of the following parameters, without combining them: the number of retransmissions, geographical area and the message expiration time. Independently such algorithms, by considering these parameters, bring an exclusive binary result: important or not.

The algorithm proposed in [8] uses the linear combination of physical distance and expiration time, to determine a binary result, establishing whether the message is important or not.

Another solution is presented in the Floating Content approach [1]. In this work, the message is maintained among several surrounding devices located in a specific geographical area without requiring a dedicated communication node. As soon as the node leaves the area, the message is removed. Thereby, this solution is also a binary one.

Even though multiple solutions for a message's importance estimation exist, they are all based on binary decisions. If conditions are met, the message is considered important. Otherwise, the message is discarded. In addition, these solutions consider only parameters separately or using linear combinations. Thus, if one parameter falls outside of the threshold, the message is considered to be non-important.

3 Background

Definition 1. *Happened before relation. The HBR, denoted by "$\rightarrow$", is the least strict partial order on a set of events E, such that:*

1. *$\forall a, b \in E$, if a and b occur in the same process, and a was executed before b, then $a \to b$.*
2. *$\forall a, b \in E$ if a is the sending of a message m, and b is the reception of m sent through a, then $a \to b$.*
3. *$\forall a, b, c \in E$, if $a \to b$ and $b \to c$, then $a \to c$.*
4. *$\forall a \in E$, $a \not\to a$.*
5. *$\forall a, b \in E$, with $a \neq b$, if $a \to b$ then $b \not\to a$.*

4 System Model

For this work, a V2I DSRC-based communication [4] is modelled as a distributed system based on a loosely coupled ad hoc asynchronous message-passing scheme. Within the system, all entities (fixed and mobile) are represented as processes. To be able to communicate both entities should be in the communication range one with respect to another.

Any process performs instantaneous executions, referred to as events: the sending and the reception of messages. This proposal assumes that for any pair of events, a causal order can be established according to the *happened before relation* (HBR) [5].

5 Indirect Spatiotemporal Communication Approach

5.1 Communication Protocol

The message dissemination between fixed and mobile entities is performed using the indirect communication protocol introduced in [3]. Concurrently, the protocol establishes the causal dependencies between each pair of exchanged messages.

The communication protocol is summarized in the following cases.

Case 1. Messages generated by fixed entity: Messages generated by communication entities embedded into the transportation infrastructure are stored in a buffer. When a vehicle approaches the fixed entity, the later sends the message to the vehicle considering its movement direction. This entity sends the message to the vehicles that are following a specific direction (one message's copy per direction). After the transmission, the message is removed from the fixed entity's buffer.

Case 2. Message received from fixed entities by vehicle: A vehicle stores into its buffer messages received from fixed communication entities. The vehicle holds the message until it can be sent to the next fixed communication entity encountered.

Case 3. Messages received by fixed entities from vehicles: These messages are handled in the following manner.

1. The message's causal conditions imposed by HBR are verified. If HBR is satisfied, the message is delivered.
2. Otherwise, the message is buffered for a Δt time.

(a) If during this time, the causal conditions become satisfied (due to other messages being received), the message is delivered immediately.
(b) If the causal conditions are not satisfied after Δt, the message is delivered, marking the previous non-delivered messages as lost.

3. After the message is delivered, it is transmitted using the same mechanism as described in Case 1.

Case 4. Messages generated by a vehicle: Messages generated by vehicles are stored separately from messages received from fixed entities until they can be sent to the first encountered fixed entity. Delivered messages are handled in the same way as other messages generated by fixed entities (Case 1).

5.2 Fuzzy-Inference System to Determine the Message's Importance

The communication protocol described above disseminates messages and ensuring that HBR dependencies are not violated. In this way, the temporal coherence of the exchanged information is guaranteed.

The message's dissemination consumes time which implies an induced delay in its delivery. How long ago an event has happened can be estimated considering the distance between the sender and receiver as well as the followed transmission path and the traffic density. This estimation can be done in a similar form as humans estimate the trip delays by considering the transportation mode and the trip length.

The less traffic density (<90 veh/km/lane), the fewer vehicles are available to transmit messages, resulting in a greater delay for message transmission. The medium traffic density (90 - 150 veh/km/lane) offers the ideal message propagation conditions as vehicles are eagerly available and their movement is not restricted by other vehicles. When the traffic density is high (>150 veh/km/lane), the vehicles move slowly. An intuitive assumption is that the vehicle's slow speed will increase the transmission delays, however, this does not happen. This effect is not produced due to the possibility of passing messages from vehicle to vehicle, thus the slow vehicle's speed has no repercussions.

In vehicular communication, a message is retransmitted, due to propagation, multiple times between fixed entities and vehicles. Each retransmission induces a transmission delay. The number of retransmission represents the dissemination path length that the message has followed.

Due to the communication protocol only considers HBR-based causal dependencies to establish a timeline to order the received messages, it is not possible to determine how long ago an event a has happened before an event b. In this paper, a fuzzy inference system (FIS) was designed to relate heterogeneous data about traffic flow and location with temporal restrictions, expressed as causal dependencies to determine the causal closeness between two events. The FIS is based on the following inference:

"How far away, how long ago and how dense the traffic is implying how close or how important the message is".

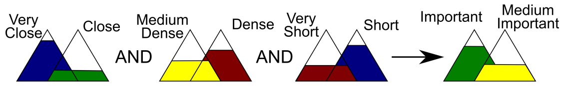

Fig. 2. Fuzzy inference system.

To estimate the message importance, we consider the following linguistic variables:

- *Path length*, whose universe of discourse is temporal data, expressed as causal dependencies.
- *Physical distance*, whose universe of discourse is the physical location.
- *Traffic density*, whose universe of discourse is the number of vehicles in a road segment.
- and *Fuzzy-causal closeness*, whose universe of discourse is the importance of the message.

The fuzzy sets, related to the four linguistic variables, are bounded as follows. The path length is bounded between 0 and 16 retransmissions. For the physical distance, the minimum and maximum values are set to 0 and 4 blocks. The boundaries for the traffic density values are 0 and 240 veh/km/lane. Finally, the fuzzy causal closeness or message importance is represented as a value between 0 and 1, where 0 means not important and 1 means very important.

By considering triangular membership functions for the fuzzy sets, the degree of fuzzy-causal closeness is determined through a Mamdani FIS [6]. The generalized version of this system is presented in Figure 2. In this way, the message's importance for a receiver can be estimated by defuzzification the outputs through a weighted average method.

6 Conclusions

This paper presents an indirect spatiotemporal short-range vehicle communication approach inspired on capillary waves. This approach extends the communication protocol [3] with the fuzzy inference system, that is designed to estimate the message's importance.

The proposed solution, determines the message's importance at each entity individually by combining heterogeneous data about traffic flow and location with temporal restrictions, expressed as causal dependencies.

An advantage of the approach is that it operates with constant communication and processing overhead and the amount of control information does not depend on the number of vehicles in the system.

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