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Cooperative Communication Disturbance Detection in Vehicle Safety Systems

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Abstract—Proactive vehicle safety systems based on vehicle-to-vehicle and infrastructure-to-vehicle communication are promising new approaches to reducing the number of accidents on our roads. In-vehicle applications are envisaged to provide a variety of services to the driver including warning about potential collisions and other hazardous situations. For the safe operation of these applications it is important not only to efficiently model the environment but also to reason about, and predict, how reliable such a model is under various circumstances. In this paper we propose an approach to estimating the reliability and availability of the wireless medium at hazardous locations by cooperatively detecting communication disturbances in order to allow for more accurate decisions by in-vehicle applications.

I. INTRODUCTION

ENABLING wireless communication between vehicles through vehicular ad hoc networks (VANETs) can bring about several new services related to safety, efficiency and comfort. Proactive safety systems that share information could help avoid or mitigate accidents by improving the short, medium and long-range situational awareness of the driver. Research into advanced driver assistance systems is carried out within a number of projects, e.g. [1], [2].

Even though less critical applications for entertainment, efficiency and comfort also are important it is the highly critical traffic safety applications that are expected to drive the market for these systems and impose the most stringent requirements.

The many different types of safety critical applications that can be provided concurrently and in real-time over an inter-vehicle network necessitate the use of a flexible and safety-conscious application platform. In [3] we outline some of the major components of such a platform.

In Section II we start by describing the need for predicting the reliability of communication at hazardous traffic locations, Section III and IV define the types of information exchanged between vehicles and how this information exchange can be used to detect *communication disturbances* (CD). Sections V and VI describe some implementation

aspects related to managing observations and CDs. We conclude the paper with a simulation of information exchange at an intersection where direct communication is impossible in Section VII and our conclusions in Section VIII.

II. COMMUNICATION QUALITY AWARENESS

Functions common to several traffic safety applications range from in-vehicle resource management to communications management. Intuitively, traffic safety applications require guaranteed access to several in-vehicle resources such as the CPU, sensors and persistent storage as well as higher level resources such as context databases. Additionally, cooperation with other vehicles is paramount in providing many envisioned safety services and this in turn is dependent on a less controllable shared resource, the wireless medium. The availability and reliability of the wireless medium is expected to be limited in several situations, requiring prioritization and choice among safety-related services depending on their importance to users in different contexts.

By assigning priorities to different classes of traffic and by monitoring the current state of the wireless medium certain fairness in attempts to access it can be guaranteed. This approach fares well in that it guarantees that available communication resources, when sparse, are used only for messages with the highest priority. However, the set of applications that is most critical is highly context dependent. For example, when approaching an intersection an application that monitors traffic light status is more important than a traffic jam application while on a highway the priorities are reversed. Thus context aware service and communication provisioning is a key component in a traffic safety application platform.

The context in this case not only concerns the specific traffic situation but also includes the availability of communication resources. In a situation where reliable communication cannot be established between two points near an intersection, perhaps due to an obstruction like a building, it is not possible to offer certain services.

To assess whether it is possible to provide a certain level of service quality it is important to be able to predict the quality of the wireless medium. Two types of propagation models exist, statistical and site-specific [4]. Statistical propagation models are typically based on large numbers of measurements made in certain types of environments, e.g.

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urban or rural, from which a general model is built for that type of environment. The more detailed site-specific models that take fine-grained topography, such as buildings and other radio wave propagation obstacles, into account are frequently too computationally demanding to be used on-line at high resolution [5]. Site-specific models are also only as accurate as their input, typically topographical maps [6], making inconsistencies between model and real world a problem.

One of the main reasons for modeling radio propagation rather than measuring it on site has been the high cost associated with deploying a network for testing purposes only. In the vehicular network scenario we expect large numbers of equipped nodes on the road at any time. In this scenario we can base our judgments and predictions on real and continuous measurements in order to detect communication disturbances caused by a variety of different phenomena. The availability of relay nodes in vehicle networks means that cooperative communication cannot only be used for transmission path diversity, as in [7], but it can also be used to predict communication availability and reliability as a function of location and time. Another approach that utilizes comparisons between shared observations in a VANET is [8] where the goal is to detect malicious data and adversaries.

This type of communication quality awareness can be used to adapt the behavior of higher level traffic safety applications, e.g. warning the driver that certain safety functionality cannot be maintained ahead.

III. THE NATURE OF OBSERVATIONS

Vehicle safety systems must be able to represent, communicate and reason about a number of objects in the domain. These objects can be divided into two main classes, physical objects such as cars and pedestrians and conceptual objects such as virtual fences or platoons of vehicles. Objects can also be either cooperative or non-cooperative depending on if they can participate in information exchange based on physical and logical communication standards or not.

A vehicle can become aware of a physical object either by observing it using on-board sensors or by receiving information about it via a radio transceiver. Once a physical object has been identified it is recorded as an observation in an onboard context database. There are two types of observations, differentiated by their origin. A *primary observation* is an observation of an object either communicated by that object itself or deduced through first-hand information from on-board sensors. Analogously a *secondary observation* is an observation of an object relayed by a third party able to observe the object directly.

The sets of primary and secondary observations make up primary and secondary contexts respectively.

Associated with each observation is a set of attributes that describe the observed and observing object as well metadata

Fig 1. Vehicles A and B cannot communicate directly because of the obstruction and use vehicles C and D to detect the disturbance.

concerning the observation itself. Examples of object attributes are identity, location, direction and velocity. Observation metadata includes a timestamp of when the observation was made as well as an indicated transmission range (ITR) which is an estimate, by the sender, of its own broadcast transmission range in the current conditions. Quality measures related to the transmission of an observation such as received signal to noise ratio and bit error rate can also be added to the observation metadata by the receiver.

In this paper we assume that all vehicles belong to the class of cooperative objects in order to highlight the use of cooperative context comparisons. However, this is a strong assumption as in the early phases of system deployment not all vehicles will be equipped. On the other hand, even without full system penetration, the existence or non-existence of non-cooperative objects, such as pedestrians or unequipped vehicles, can still be determined in the vicinity of cooperative vehicles by using on-board sensors such as radar and cameras.

The temporal resolution of the context databases is dependent on the frequency of observations received from other cooperative objects. In its simplest form vehicles transmit discrete location updates but a more refined format can also be envisioned. For example, vehicles could transmit trajectories represented by spline coefficients [9] which would provide a much more detailed representation of their locations over time.

IV. COMMUNICATION DISTURBANCE DETECTION

Fig. 1 illustrates a scenario where inter-vehicle cooperation can be used to detect current communication conditions. Four vehicles, A, B, C and D are approaching a four-way intersection from the north, west, south and east respectively. Each vehicle is equipped with a radio transceiver and continuously broadcasts its own location. In addition to informing other vehicles about themselves each vehicle also retransmits the primary information it has concerning the location of other vehicles in the vicinity.

In this scenario all vehicles are within ITR of each other, however there is a tall building between vehicle A and B that causes non-line-of-sight (NLOS) conditions leading to a situation where vehicles A and B are unable to communicate directly with each other. However, after receiving secondary observations about each other from C and D all vehicles will be aware of each others locations.

By comparing primary and secondary contexts A and B will now be able to deduce that they were unable to communicate directly at a point in time when they were both located within each others ITR. We call this discrepancy between primary and secondary observations a *communication disturbance* (CD).

We define the set of CDs more formally in (1).

$$CD = \{(c,o) \mid c \in C, o \in O, itr(c,o)\} \quad (1)$$

$$C = \{S \setminus P\}$$

Where P and S are the sets of primary and secondary observations respectively, O is the set of each vehicles own positions recorded over time, C is the set of candidate observations and $itr(c,o)$ indicates that a candidate observation c was made within transmission range and in temporal proximity of the vehicles own position indicated by observation o . Fig. 2 illustrates the contents of the various sets for a four-node scenario.

CDs can indicate a number of circumstances:

- Obstacles in the environment, both static and dynamic
- Path loss due to environmental conditions such as rain and snow
- Equipment properties such as unexpected antenna radiation patterns
- Overload situations
- Radio wave interference and noise

Over time vehicles will help each other to detect and accumulate CDs as they travel throughout the road network. In order to draw any conclusions about recurring communication weak-spots such discrepancy information must be collected and aggregated from many vehicles and over relatively long periods of time. We expect the validity of observed discrepancies to vary depending on the dynamicity of the phenomena that caused the communication problem. For example, in the illustrated scenario the tall

Fig 2. CD detection in four node network at time t . All nodes except V_1 and V_2 can communicate directly with each other. The contents of the observation sets for node V_1 at t is: $P=\{V_3, V_4\}$, $S=\{V_2, V_3, V_4\}$, $O=\{V_1\}$, $C=\{V_2\}$, $CD=\{(V_2, V_1)\}$

building is a static cause of communication discrepancies and will hence most likely generate further discrepancies between vehicles approaching from the north and west.

In order to clearly present the concept of CD detection we intentionally limit the scope by only talking about the logical existence or non-existence of observations when detecting discrepancies. However, additional information can be used to reason about the communication quality such as received signal strength indicator (RSSI) measurements, packet loss and bit-error rate (BER). Using this type of information provides an even more fine-grained view than what can be achieved by only considering complete communication failures. Situations in which communication is possible but is degraded, e.g. due to transmission rate adaptation or other lower layer functions, are expected to be as important to communication quality awareness as complete communication failures.

V. AGGREGATION OF OBSERVATIONS

Aggregation of CDs is performed centrally by a server and consists of accumulating CDs detected by nodes in the network. The observations are then made available to vehicles based on the specific area they are traveling in. For such a service a suitable representation format must be chosen that supports storing large numbers of CDs between pairs of geographical locations.

Mobility in vehicular networks is constrained by the road topology and hazardous situations are in many cases associated with certain geographic locations, such as intersections and pedestrian crossings. CD storage and aggregation methods need to take these constraints into account in order to reduce the computation and storage complexity. A concrete way to do this is to employ variable resolution radio maps, with increased resolution in regions

with high spatial variability in detected communication quality.

The variability of the phenomena that cause CDs influences to what degree the aggregation process can be centralized. For static obstacles, such as buildings, communication quality maps can be constructed and distributed to vehicles entering an area. This type of long-term data gathering means that CD detections still are usable even if they are not uploaded to a central server immediately, e.g. when there is no long range infrastructure available in the direct surroundings. In order to utilize the most economical carrier, both in terms of monetary cost and bandwidth, for uploading CD detections vehicles can utilize infrastructure such as Wi-Fi hotspots when parked.

In the case of more dynamic phenomena such as rain or snow highly centralized aggregation is less suitable. However, local infrastructure can be co-utilized as short-term aggregation points at certain locations. For example road-side infrastructure deployed around an intersection can both relay observations and provide short-term reports on how vehicles have perceived the communication quality in that specific area recently.

VI. PRUNING OBSERVATIONS

Observations are expected to accumulate quickly and there is a need for primary and secondary context pruning. This is achieved by focusing on the most recent primary and secondary observations and cutting past or historic observations after some time. In our simulations we use a pruning strategy based on removing observations that are older than a specific threshold value. Properties of a more elaborate pruning algorithm include the ability to remove observations that are least likely to be part of future discrepancy detections as well as being able to remove observations in such a way that it does not introduce discrepancies artificially. For example, if a primary observation of a vehicle at time t is simply removed from the context database and there exists a secondary observation of the same vehicle at the same time t , the secondary observation would be included in the set of CDs as defined in (1).

Whether a discrepancy will be introduced when removing a primary observation cannot be directly checked based on the contents of the context database, since related secondary observations may arrive after the primary observation has been pruned away. One way of addressing this problem is to associate observations with an expiration time that could be used to keep old observations from propagating in the network. In our simulation this situation is addressed by allowing primary observations to remain in the context for a longer duration of time.

Obviously a recent primary observation is expected to be more relevant than an older primary observation as there is a connection between its temporal and spatial properties. A recent primary observation implies that both vehicles are in

the vicinity of each other. Further, in [10] the requirements of several safety critical applications are listed and the maximum hop count seldom exceeds more than three hops.

When detecting CDs the existence of one or more secondary observations not corroborated by a primary observation is the main indicator of a communication problem. Assuming that vehicles only retransmit their own primary observations, i.e. messages can only travel two hops, the only other vehicles that can form a CD from a specific observation is the set of vehicles that were within ITR of the sender at the point of transmission. Only if vehicles within this set have low relative velocities in relation to the primary observer should the observations be stored for an extended period of time. When vehicles are not traveling in the same direction, the set of interested parties will quickly disperse.

VII. SIMULATING DISTURBANCE DETECTION

We have constructed a simulator to analyze the impact of CD detection in communicating vehicle systems. The simulator is written in Java and uses a topographical map to simulate an 800m by 800m area with two one-way roads intersecting in the middle. Communication between vehicles approaching from the west and north is blocked by a building similar to the situation depicted in Fig. 1.

The communication model is simplified to illustrate cooperative behavior at the application level. All vehicles have a uniform maximum communication range. Vehicles within communication range can exchange information as long as they are within line-of-sight (LOS) of each other. Non-line-of-sight (NLOS) conditions between two vehicles means that no communication is possible between them at all. When determining LOS conditions only the topography of the environment is taken into account, i.e. vehicles themselves do not cause NLOS conditions. The medium access control (MAC) approach is to delay transmissions by a random value if the channel is busy modeling the carrier sense multiple access (CSMA) back off scheme, otherwise no collision detection is implemented. Transmission is modeled by having a transmitting node occupy the channel for a fixed amount of time.

As discussed in the previous section vehicles only retransmit observations from their primary context which means that messages travel at most two hops in the network. Each vehicle detects CDs locally and they are aggregated in a global CD database, which simulates vehicles uploading discrepancy detections to infrastructure.

In the simulation vehicles approach the intersection from the north and west at a constant average rate with exponentially distributed inter-arrival times. All vehicles have a uniform speed of 20 m/s.

In order to emulate a context-aware collision warning application the areas that vehicles travel immediately before entering the intersection have been defined as approach zones. Each approach zone covers the entire width of the lane and is 120m long. Only CDs that consist of pairs of

observations between the two approach zones are counted as relevant for vehicles approaching the intersection. The number of detected CDs relative the number of successful direct communication attempts between the two approach zones at the intersection gives vehicles an indication of how reliable other vehicles have been able to communicate there previously

In order to measure the impact of primary (one-hop) and secondary (two-hop) observations in perceiving the context we allow vehicles to collide at the intersection and analyze whether the accident could have been avoided based on the timeliness and type of information available in each vehicle prior to the collision. We call a collision between vehicles A and B *avoidable* if vehicle A or B had primary or secondary observations of each other at least t_s seconds before the collision. t_s is a safety margin which in our simulations is set to two seconds. A two-second safety margin corresponds to a 40m distance to the point of collision, enough distance for a vehicle to come to a complete stop when traveling at 20m/s on dry asphalt.

Fig. 3 shows how the number of avoidable accidents due to vehicles having primary or secondary observations of each other varies with average vehicle arrival rate and transmission range. It can be noted that when the traffic volume is high the timely propagation of observations for accident avoidance is degraded; this is mainly due to congestion of the wireless medium and hidden terminal interference. Analogously in sparse traffic there are not enough vehicles to relay observations, with the direct

communication path blocked this leads to a poor view of the environment. Accident avoidance due to primary and secondary observations is at its highest when the average vehicle interspacing is close to the radio transmission range, i.e. when the network is still connected yet has low medium congestion and hidden terminal interference.

During high volume conditions limiting the transmission range greatly improves information propagation during high volume traffic since the medium becomes less congested. However, during low volume conditions without primary communication possibilities the transmission range adaptation yields less of a benefit due to the lack of relay nodes. To warn the driver that there exists poor direct communication abilities and that during high and low volume conditions vehicles may not be detected before colliding, CD detection can be used.

In Fig. 4 we show the average number of CDs detected per minute as a function of average vehicle arrival rate for a fixed transmission range of 300m and note that CD detection frequency approximately depends on traffic volume in the same way as secondary observation propagation. Since CD detection is based on the availability of secondary and primary observations this is expected. However, even at high traffic volume roughly 20 CDs are detected per minute.

At low volumes CD detection fails since there are not enough cooperative nodes to compare contexts with. As traffic volume varies at locations over time it is expected that enough disturbances can be detected to be able to draw conclusions about direct communication failures. However,

Fig 3. The ratio of avoidable accidents to all accidents as a function of average vehicle arrival rate for four different transmission ranges

at sites with continuously low traffic volumes such as rural intersections this may not be possible. Vehicles can still draw conclusions from the lack of reliable observations made at a hazardous traffic location by observing that very few observations, of successful communication as well as disturbances, have been made at that location. When approaching such an uncharted area traffic safety applications are informed that there is not enough information to judge the reliability of communication between vehicles at that location.

To improve CD detection as well as information relaying at a low traffic volume location infrastructure can be deployed to act as a local CD aggregation point and relay node as mentioned in Section V. Reports of poor communication quality or very low traffic volume could additionally be used in the planning stages as indicators of where to focus infrastructure deployment.

VIII. CONCLUSION

The results indicate that in conditions when vehicles are unable to communicate directly with each other the availability of network nodes, infrastructure or vehicles, which can relay information is crucial in perceiving the environment. Further, both high- and low-volume traffic conditions affect the relaying of secondary observations by delaying and interfering with information exchange. The proposed method for detecting communication disturbances can be used to discover and react to these conditions by utilizing observations made previously by other vehicles and uploaded to centralized infrastructure.

The primitive approach to media access control is one of the causes of congestion at higher traffic densities. However, even with more sophisticated MAC schemes there will still exist situations in which the medium will be congested at a hazardous traffic location. When vehicles approach such a location it is important to judge how reliably they can come to know of each other through wireless communication.

We have shown that by cooperatively comparing primary observations (received directly from vehicles) with secondary observations (shared primary observations) a communication quality measure can be made at hazardous traffic locations, exemplified by an intersection where direct communication is blocked by a building. This quality measure is important for higher level decision logic concerned with providing context-specific warnings to the driver.

REFERENCES

- [1] European Commission, 6th Framework Program Subproject, "Cooperative Vehicle-Infrastructure Systems, CVIS", <http://www.cvisproject.org>, January 2007.
- [2] European Commission, Information Society Technologies, 6th Framework Program Subproject, "SafeSpot: Cooperative Systems for Road Safety", <http://www.safespot-eu.org>, January 2007.

Fig 4. CD detection frequency as a function of average vehicle arrival rate for a fixed transmission range of 300m.

- [3] K. Lidström, T. Larsson, and L. Strandén, "Safety Considerations for Cooperating Vehicles using Wireless Communication", in *Proc. 5th IEEE International Conference on Industrial Informatics*, July 2007.
- [4] T. K. Sarkar, Z. Ji, K. Kim, A. Medouri, and M. Salazar-Palma, "A Survey of Various Propagation Models for Mobile Communication", in *IEEE Antennas and Propagation Magazine*, vol. 45, June 2003.
- [5] R. J. Punnoose, P. V. Nikitin, J. Broch, and D. D. Stancil, "Optimizing Wireless Network Protocols Using Real-Time Predictive Propagation Modeling" in *Proc. IEEE Radio and Wireless Conference*, August 1999.
- [6] T. Kürner, D. J. Cichon, and W. Wiesbeck, "Concepts and Results for 3D Digital Terrain-Based Wave Propagation Models: An Overview", in *IEEE Journal on Selected Areas in Communications*, vol. 11, September 1993.
- [7] A. Nosratinia, T. E. Hunter, and A. Hedayat, "Cooperative Communication in Wireless Networks", in *IEEE Communications Magazine*, October 2004.
- [8] P. Golle, D. Greene, and J. Stanton, "Detecting and Correcting Malicious Data in VANETs", in *Proc. 1st ACM International Workshop on Vehicular Ad Hoc Networks*, October 2004.
- [9] B. Yu, S. H. Kim, T. Bailey, and R. Gamboa, "Curve-Based Representation of Moving Object Trajectories", in *Proc. International Database Engineering and Applications Symposium*, 2004.
- [10] C. L. Robinson, L. Caminiti, D. Caveney, and K. Labertaux, "Efficient Coordination and Transmission of Data for Cooperative Vehicular Safety Applications", in *Proc. 3rd International Workshop on Vehicular Ad Hoc Networks*, September 2006.