Field Measurements of IEEE 802.11p Communication in NLOS Environments for a Platooning Application

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Abstract: **This paper presents results from field measurements on a vehicle-to-vehicle communication system based on IEEE 802.11p. During the measurements the vehicles were moving and there were also moving obstacles located between the transmitting and receiving nodes creating a Non-Line-of-Sight environment. Distance, speed and type of obstacles were varied during the measurements. Both a highway and suburban environment was tested. The tests were focused on packet error rate and consecutive packet loss. The results of the measurements are compared with the communication requirements of a vehicle platooning application which is a novel intelligent transport system application. It implies multiple vehicles tightly following each other in a row. Performance of the application degrades with consecutive packet loss. It is shown that the platooning application is not adequately supported in all measurement scenarios.**

Keywords: V2V, IEEE 802.11p, Field Measurement, Drive Test, Packet Error Rate, Consecutive Packet Loss, Vehicle Platooning

I. INTRODUCTION

Vehicle infrastructure in the world will dramatically change in coming years. Higher traffic intensity, environmental considerations and increasing fuel prices will force vehicles and the supporting infrastructure to be more efficient. The cost of accidents and traffic jams is already significant and will probably increase in the future. This in combination with advances in wireless communication is the driving force behind a new intelligent infrastructure for vehicles [1]; also known as ITS (Intelligent Transport Systems). The wireless communication system for this infrastructure is not decided yet, but there are candidates such as IEEE 802.11p, 3G, LTE or a combination of these. The communication platform in this paper is based on IEEE 802.11p which is an amendment to the IEEE 802.11 standard to add Wireless Access in Vehicular Environments (WAVE). It proposes small modifications to the PHY and MAC layers (compared to 802.11a) in order to achieve a robust connection and a fast setup for moving vehicles. IEEE 802.11p transmits in the licensed 5.9 GHz band [2] which has been allocated for ITS-applications. It is divided into 7 channels where each channel has 52 sub-channels. The standard is Half-duplex: a station can send or transmit, but not both at the same time. It supports up to 27 Mbps.

In recent years several groups have studied Vehicle to Vehicle (V2V) communications using IEEE 802.11p in different scenarios [3-8]. In [3-5] communication is characterized in a mix of Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions focusing on parameters such as channel gain, path loss, coherence time, power delay profile and Doppler spread. In [6] the focus is on channel measurements at street intersections for V2V safety applications. Paper [7] presents range measurements for vehicles driving towards or away from each other. However, in papers [3-5] the results are not presented per type of propagation channel, but rather as an average or combination over different propagation channels. Papers [6 and 7] distinguish between LOS/NLOS scenarios, but are limited to NLOS situations created by buildings located close to street intersections or other stationary objects.

A survey of V2V communication is done in [8]. Different propagation channels, channel characteristics such as path loss exponent, delay spread and Doppler spread are compared for different types of roads: highway, rural, suburban and urban. It is shown that the channel characteristics vary depending on the type of road; which can be explained by the different velocities, surroundings (number of and distance to scatterers differs in open areas versus small cities), traffic intensity etc. All these variations affect the multi path environment which in turn affects the channel response.

In our paper results from V2V measurements in different traffic scenarios and road environments are presented per road environment, vehicle speed and LOS/NLOS situation. NLOS situations studied here is created by an obstructing vehicle located between a transmitting (Tx) and a receiving (Rx) vehicle. The NLOS situation caused by a moving vehicle significantly differs from NLOS situation that is caused by a building [6]. The scenario with obstructing vehicles is plausible in several traffic situations and can occur with relatively short distances between the vehicles. Some examples of situations where NLOS occurs are listed below:

- In multi hop communication source and destination nodes communicate via one or more intermediate nodes. The source and destination nodes do not require being in LOS. If an intermediate node suddenly suffers from communication failure a NLOS situation will likely be created.

- In a platooning scenario, i.e. multiple vehicles tightly following each other in a row, the intermediate node(s) will also shadow the direct radio path.
- During roll-out of V2V communication technology there will initially be a small number of equipped vehicles. This implies that V2V equipped vehicles will be sparsely distributed and communication will therefore be mainly be NLOS.
- Extra equipment mounted on the vehicle such as other antennas, roof-rails etc. or a temporary towed trailer or container will change the radio propagation path and possibly create NLOS situation. This is valid for both trucks and cars.

Another reason to study NLOS performance is the ability of the nodes to receive information beyond the immediate traffic environment, e.g. beyond visual range hence NLOS. Such information helps the vehicle to gain knowledge of the present local traffic situation and is important e.g. for safety applications.

Platooning is a novel ITS-application where V2V communication is an essential part. Results with measurements and tests of the V2V system, including a comparison of antenna placement, have been published [9]. This paper contributes to the understanding of how to design a reliable V2V system for platooning and also the V2V characteristics that the platoon control system must be designed to handle

This paper is organised as follows: Section II describes the SARTRE platooning application. Section III describes the methodology of the experiments. Section IV describes the results and finally Section V concludes the paper.

II. SARTRE PLATOONING APPLICATION:

SARTRE (SAfe Road TRain for the Environment) is a project which develops technology for platooning [10, 11]. It is a European Commission Co-Funded FP7 project that seeks to support a step change in transport utilization. The project vision is to develop and integrate solutions that allow vehicles to drive in platoons. SARTRE defines a platoon (or road train) as a collection of vehicles led by a manually driven heavy lead vehicle. The following vehicles (trucks and passenger cars) follow the lead vehicle automatically; both laterally and longitudinally. Vehicles may join or leave the platoon dynamically e.g. leave on arrival at the desired destination. SARTRE aims to explore technology for platooning on roads without changes to the infrastructure and that it is safe enough to allow mixing with other users of public roads. Expected advantages of platooning include a reduction in fuel consumption, increased safety and increased driver convenience and comfort.

The technical challenges in the project are many and interesting such as the design of control algorithm and sensor-fusion. Another challenge is the V2V communication system. The V2V node is a wireless gateway between the network in the local vehicle to the networks in the other vehicles. In SARTRE the vehicle networks are CAN, but this may likely be FlexRay or Ethernet in the future. The V2V node allows sharing of local vehicle signals such as speed and sensor data among vehicles in the platoon. The shared signals are used in the control algorithms of the platoon. The platoon forms a cooperative system where sensing, control algorithm and actuation are distributed throughout the platoon and data is communicated between vehicles (V2V). Automatic control over an individual following vehicle is partly external from the lead vehicle and partly internal from the systems in the following vehicle itself. The following vehicles automatically strive to maintain the specified gap to the vehicle in front, and the trajectory as specified by the lead vehicle. The local systems in the following vehicle can also take over in emergency situations and during loss of communication. Another aim is therefore to maintain the gap at a size which discourages interference from other vehicles, i.e. driving inside the platoon.

The platooning application requires that V2V communication is used in addition to local sensors in each vehicle. Using V2V implies that data can be sent directly from the source rather being indirectly measured locally with sensors. Detecting platoon movements via only local sensors is prone to lag and to accumulate errors. This is because local sensor measurements are only based on the adjacent vehicle, i.e. there is no “look ahead” e.g. of intended movements. For example the lead vehicle can directly send requested acceleration as measured at the pedal rather than having a following vehicle measure the acceleration with its local sensors. With local vehicle sensors a change in acceleration has to “propagate” through the platoon from the lead vehicle to each of the following vehicles and be detected. This affects, for example, the minimum gap size that can be safely achieved. Without V2V it has to be larger gap to allow for the slower response. Using only local sensors can lead to lateral and longitudinal instability, increased oscillations, and unsafe behaviour of the platoon.

The goals of longitudinal control, e.g. the speed of the following vehicles, are to make coordinated movements that are accurate and adequately safe. Two examples are keeping a fixed gap between vehicles and being able to perform an evasive manoeuvre such as emergency brake or lane change. Lateral control (steering) has similar goals, solutions and also faces similar challenges.

The local and V2V data is combined by sensor fusion. The default weight of each source is decided offline; V2V data is preferred. The weighting is adapted during operation e.g. with regard to operating conditions such as speed of the platoon. V2V data is more prone to transient communication failure compared to the local sensor data. Sensor fusion is therefore used and is adaptive according to the condition of data. The current reliability of V2V data is assessed by two means: timestamps and an update counter. The sender of a message adds a timestamps with the current time. The message contains multiple signal data. The receiver can hence detect that the signals have not been updated as expected and are hence old and less valid. The message also has a counter that is incremented each time the message is sent.

The V2V node also generates a V2V status signal that states the reliability, from 15 (the highest) down to 0, of the wireless connectivity between the local V2V node and the other V2V nodes in the platoon. The signal gives a general statistical measurement of V2V reliability but is not related to any particular data. Low V2V status indicates that V2V connectivity is probably not reliable, e.g. high packet error rate.

When V2V data is available a fall-back strategy ensures that platoon operation is still safe. The strategy has four classes with gradual loss of trust depending on the length of the communication-loss epoch, i.e. a time period where no correct messages are received - consecutive packet loss: 1) For V2V failure epochs that are shorter than 200 ms, nothing is done; 2) For V2V failure epochs between 200 ms and shorter than one second, modified control parameters are used based on the last valid V2V data. Safe assumptions are made e.g. about acceleration until V2V communication is resumed; 3) For V2V failure epochs that are between one and three seconds, the inter vehicle gap is smoothly increased; 4) Eventually, after three seconds of V2V communication loss dissolution of the platoon is initiated. Platoon dissolution implies manual take over by the drivers in the following vehicles.

The time parameters for the fall-back strategy and other parameters related to the control system are found as currently being investigated as part of development and field tests. Human factor (response time for manual take over) and comfort (inconvenience of premature platoon dissolution) has to be taken into account in addition to safety. The time parameters given above are therefore examples and reasonable assumptions, and are subject to change. Characterisation of V2V performance parameters is also found in field tests, such as presented in this paper. Examples of parameters are range, Round-Trip Delay (RTD) and consecutive packet loss. These parameters vary with the conditions for the tests. This knowledge contributes to the reliability of the platooning system since e.g. control algorithms can be designed appropriately by taking into account the properties of the V2V system.

III. EXPERIMENTAL METHODOLOGY

This paper presents results from field tests performed at two different test routes: one suburban road; and one highway. These routes were driven by two vehicles with IEEE 802.11p communication equipment. The NLOS condition was created by a third vehicle driving in between them. In the field test the Packet Error Rate (PER) is characterized (i.e. both erroneous packets and transmitted but not received packets) and the consecutive packet loss is measured in different tests.

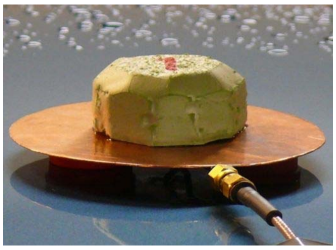

Figure 1: Monopole antenna mounted of the roof of a car.

A. *Test setup*

Nodes from the CVIS project [12] were used together with test software developed at SP Technical Research Institute of Sweden. The nodes transmit according to the standard [13] in the ITS-band (5.850-5.925 GHz). The output power from the node was measured at SP and found to be 16.5 dBm (nominally 17 dBm according to the node configuration). This level complies with the EIRP power limit (23 dBm) of the channels that are used, i.e. SCH1 and CCH of the ITS-G5A safety applications band [13]. This implies that an antenna with a gain up to 6.5 dBi can used. Two CVIS nodes were used in the setup; a server node and a client node. Both had the CVIS distribution R8 of the Linux OS. The 802.11p radio chip in the communication nodes are Atheros AR5414 and the radio boards were manufactured by QFree. The raw data-rate of the channels are 6Mbit/s (default). During operation the client sent messages of size 100 bytes at 10 Hz (i.e. a messages is sent every 100 ms) to the server which in turn echoes them back to the client. The client logged time and date of the sent messages and compared these with the returned messages to calculate RTD for each message and the packet error rate. Sent messages that were not returned were also logged so the number of consecutive lost packets could be found off-line.

The antennas that were used in the tests are quarter wavelength monopoles (custom made by SP) mounted on a circular ground plane (radius approximately 50 mm). Fig. 1 shows the constructed antenna and how it is mounted on the roof top of a car. Monopole type antennas have a so called donut-shaped radiation pattern and a theoretical gain of 5.16 dBi. The antenna type is considered to be a good reference as it is easy to model thus enabling future studies in more detail. The block on the circular ground plane in Fig. 1 is a radome constructed from Styrofoam protecting the monopole and does not affect the antenna performance. The antennas are carefully matched to 50 ohm in the ITS band.

Before the tests the equipment was checked by measuring the communication range on a straight road at very low speed and with LOS, see Fig. 2. One vehicle was parked and the other drove away slowly (~10 km/h). The maximum communication range before all packets were dropped was approximately 400 m, see Fig. 2. At a first glance this might seem a bit short for ITS-applications, and the range could actually be improved by using antennas with higher gain or by increasing the send power. However, antennas with higher gain in some directions will have low gain in others. This will result in week signals in some scenarios e.g. during communications

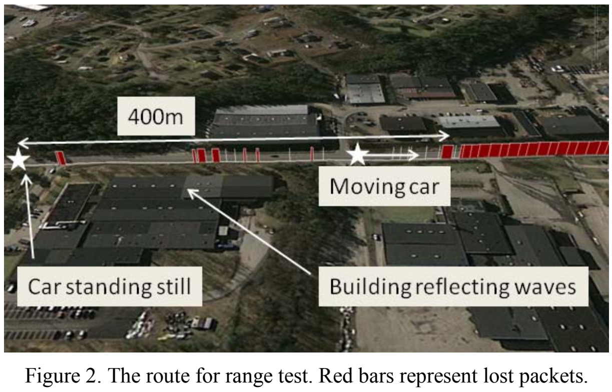

Figure 2. The route for range test. Red bars represent lost packets.

Van Small truck

Ordinary truck Large container truck

Figure 3. Typical sizes of trucks and van

above or below the horizontal plane, a situation which will occur when a low car communicates with a truck with the antenna mounted on the roof. Therefore high gain is not always the best solution. During the range measurement, packets were lost already at 200 m. The reason for this is multipath propagation, which probably was generated by a few strong waves reflected in walls of nearby buildings [14, Ch. 2], see Fig. 2. In such scenarios diversity [14, Ch. 7] at the receiver would be useful.

B. Test routes

Two different routes were defined for the tests: A suburban road and a highway. The suburban road extends through industry properties, residential areas and passes both roundabouts and crossings. The highway consists of two parallel lanes in each direction separated by a steel crash barrier in the middle and is located in the country side. The speed of the vehicles at the suburban road was in the interval 30 - 50 km/h and on the highway the speed was approximately 110 km/h. During the tests both cars were moving in the same direction. The performed measurements are shown in Table I. Column *Setup* in the table describe the vehicle setup during measurement, e.g. “Tx–Rx” means only Client and Server cars and “Tx–*Vehicle*–Rx” means a vehicle is disturbing communication between client and server cars, i.e. causing a NLOS environment. Descriptions of disturbing vehicle are found in column *Setup*, of Table I and in Fig. 3.

IV. RESULTS

PER from the field tests are summarized in Table I. Suburban road tests S1 and S2 show that communication works very well when no object is blocking LOS and PER is less than 1%. For measurement S1 the distance between the vehicles was approximately 33 m and the speed was 40 km/h. In S2 the distance between the vehicles was approximately 17 m and this shorter distance resulted in PER as low as 0.1%. When a small truck is located between the client and the server vehicles on the suburban road messages starts to be lost more frequently and PER becomes 7.3%. In this setup LOS is almost permanently blocked by the truck and the distance between the client and the server was approximately 33 m. The reason for this under the circumstances relatively good PER are waves reflected in the surrounding environment creating a (poor) multipath environment. In highway measurement H1 there is no disturbing vehicle and the nodes can communicate in LOS. Even in these good conditions PER is as high as 17%. In measurement H2 LOS is only slightly blocked by another vehicle (a station wagon) of approximately the same height. This obstruction is however enough for PER to rise to 40%. In measurement H3 LOS is now blocked by a van and PER was 81%.

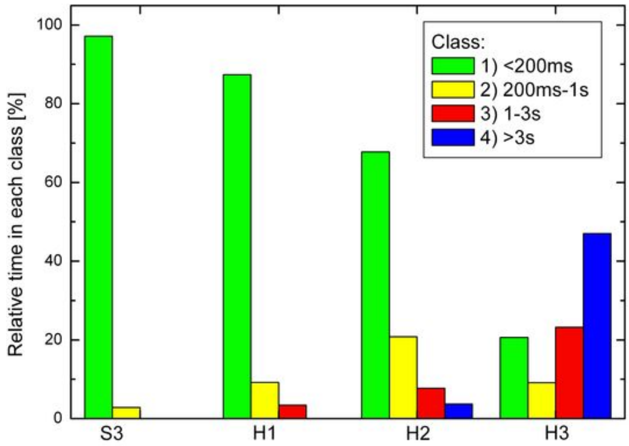

Figure 4: Consecutive packet loss for test S3 and H1-3

Finally, in measurements H4 and H5 performed on the highway LOS was blocked by an ordinary truck (H4) and a large container truck (H5), respectively. PER in these measurements is about 96%. There are multiple reasons for the high PER in measurements H1-H5. NLOS caused by disturbing objects is one and high delay spread due to multipath propagation and high speed is another. Finally a reason is fact that the distance between the Client and Server cars is quite large compared to the possible communication range.

The number of consecutive lost packets is of importance for the platooning concept [10] and other cooperative applications such as adaptive cruise control. Even if the PER is relatively low the application can suffer if several consecutive packets are lost. Consecutive packet loss for tests S3, H1, H2 and H3 is shown in Fig. 4. The other tests are omitted as they are deemed

TABLE I: TESTS AND RESULTS

Test no.	Road	Speed [km/h]	Setup	Distance Tx to Rx* [sec.]	Distance Tx to Rx* [m]	Classification	PER [%]
S1	Suburban	30-50	Tx – Rx	3	33	LOS	1
S2	Suburban	30-50	Tx – Rx	1.5	17	LOS	<0.1
S3	Suburban	30-50	Tx – Small truck – Rx	3	33	NLOS	7.3
H1	Highway	110	Tx – Rx	6	180	LOS	17
H2	Highway	110	Tx – Station wagon type car – Rx	6	180	NLOS	40
H3	Highway	110	Tx – Van – Rx	6	180	NLOS	81
H4	Highway	110	Tx – Ordinary truck – Rx	6	180	NLOS	96
H5	Highway	110	Tx – Large container truck – Rx	6	180	NLOS	96

*Reported distance is from Rx-node to Tx-node, i.e. the distance to an optional disturbing vehicle is half that distance.

to have either too low PER (S1 and S2) or too high PER (H4 and H5) to be of interest, see Table I. Class 1 allows single lost packets but no consecutive loss. Class 2 implies 2-9 consecutively lost packets. Class 3 implies 10-29 consecutively lost packets and Class 4 more than 30 consecutively lost packets. According to the class definitions of the SARTRE platooning application in Section II, platooning will be successful in the environments of test S1-3 and H1, but mainly unsuccessful in H2-3 and H4-5. This is because the platoon will dissolve due to the inadequate number of received packets, i.e. the communication quality is too low.

The RTD for of the successfully transmitted *and* received messages was measured in tests S1-3 and H1-5. It was >2ms for more than 90 % and 80% respectively and always less than 4ms. This is acceptable for the platooning application.

V. Conclusions

The tests in the suburban environment (S1-3) showed lower PER and consecutive packet loss than the test in the highway environment (H1-5). At the suburban route the multipath environment is clearly utilized as reflected waves are received when the truck is blocking the LOS (S3). If diversity was implemented (e.g. two receiving antennas) PER would probably be improved [14, Ch. 7]. Many lost packets in the highway measurements imply that communication suffers from Doppler shift at high speeds and/or a poor multipath environment. At the highway reflected rays might be too weak in signal strength to be utilized, reason for this is that the distance between cars increases as the speed gets higher. Reflected paths will now be very long compared to possible transmission range. This highway was located in an open area resulting in long distance to any reflecting object other than the crash barrier. Normally buildings, trees etc. are not located in the direct vicinity of a highway which results in long distances to any scattering object. Antennas with designed radiation patterns (e.g. more gain in horizontal plane) could perhaps solve this range problem. The trade-off is that such antennas will be more sensitive when receiving signals above or below the horizontal plane. To avoid NLOS situations on the highway diversity [14, Ch. 7] or MIMO [14, Ch. 10] could be used. This would benefit not only from the multi-path environment at the highway, but also to avoid radio shadows created by disturbing vehicles. Diversity with antennas under and over the car would be interesting to test as well as antennas mounted in/on the rear view mirrors.

We also conclude that all of the suburban tests (S1-3) and one highway test (H1) would support platooning according to our definitions. In the other highway tests (H2-5) the number of consecutively lost packets is too great to adequately support platooning. Note however that tests H2-5 are situations where a platoon contains an unwanted other vehicle that is not part of the platoon, i.e. this is a situation that SARTRE concept [10] strives to avoid. The SARTRE platooning concept is designed to travel at 85 km/h due to the sped limit of the trucks in the mixed platoon. This speed is lower than the speed in test H1-5 and PER would probably improve somewhat at a lower speed.

Steps can be taken to improve the system reliability in the platooning application: The V2V-communications could be made more reliable (e.g. improved antenna design and better antenna placement) or; the control application can be modified (increased transmission rate of data or increased gap).

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