Cooperative Communication Network for Adaptive Truck Platooning

Razvan Andrei Gheorghiu, Valentin Iordache and Angel Ciprian Cormos
Transport Faculty, Electronics Dept., "Politehnica" University of Bucharest, Splaiul Independentei, Bucharest, Romania

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Abstract: Truck platooning represents a solution to increase energy efficiency of the freight road transport. This method assumes very little distance between trucks so that overall aerodynamic quotient is improved. However, this requires a specific and dedicated infrastructure, due to the fact that the total length of the convoy may be considerable, which has a negative impact on the general traffic: other vehicles need a lot of space (and time) to overtake the platoon and this can only be done on highways with more than two lanes / direction. This means that in most cases (national roads and less wide highways) platoons cannot be formed and this method cannot be implemented. To resolve this situation, in this article we have proposed a solution for dynamic platoon formation, based on vehicle-to-vehicle communications, that will allow other vehicles to gradually overtake the vehicles forming the platoon. For this, a communication technology proposal has been made to ensure the identification of vehicles that are obstructed by the platoon. We have also made a series of laboratory measurements to test the validity of the proposed solution and, in the end, presented our conclusions.

1 INTRODUCTION

Vehicle platooning is a relatively new concept that can provide many benefits, such as improved vehicle safety, improved fuel consumption due to less aerodynamic drag (and, hence, reduced environmental pollution) (Kavathekar, 2012).

For the realization of the platoon, the vehicles composing it must have fully automated longitudinal and lateral control to be able to maintain the same spacing between all platoon members at all speeds, as they travel through the road network. This kind of automation increases safety for all involved vehicles. With very small headway spacing, as little as a few meters, the vehicles follow each other. The key element is a very reliable communication system: the lead vehicle (LV) of the platoon continuously broadcasts to the following vehicles (FV), information on the maneuvers that the platoon is going to execute.

This approach is highly studied and there are many details provided on what systems need to be put in place to create a platoon and how the communications between vehicles should be implemented to ensure the minimum distance between vehicles (European Commission, 2014; Bergenheim et al, 2012a; Bergenheim et al, 2012b; Janssen et al, 2015). Platooning concept has been tested in real life conditions in several projects, such as SARTRE (SARTRE-Consortium, 2012), PATH (Lu and Shladover, 2011; Nowakowski et al, 2015) or KONVOI (Institute for Automotive Engineering, 2009).

But all approaches, as far as our knowledge, refer to the creation of a platoon with fixed distance between vehicles. Studies have shown even the necessity to implement a dedicated infrastructure for this type of road train. This is a proper approach when we consider only the fuel economy and the other benefits of platooning without caring for price. This solution is very expensive to implement and it can't be used for most of the existing roads due to the fact that for longer platoons it is very difficult for other vehicles to overtake the vehicles in the platoon.

The concept of vehicle platooning may be applied to all the vehicles but, as energy efficiency is the primary goal of this concept, we shall analyze only the truck platooning concept in the rest of the article, considering that for the other types of vehicles this desiderate is not the primary goal. Also, in order to simplify the first concept of the system, we shall consider only the highway scenario, as platoon formation on national roads imply even more challenges and issues that have to be further analyzed.

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This desiderate can only be achieved when there is a certainty that all the vehicles travelling that road have autonomic capabilities, which, for sure, will not happen in the near future.

2 DYNAMIC PLATOONING CONCEPT

2.1 System's Concept

Dynamic platooning is a method of platoon formation for which the distance between vehicles is not fixed. The distance tends to be minimum when other vehicles are not around, but gaps may be formed in the platoon to let outside vehicles (OV) travel without obstruction from the platoon.

We shall consider two scenarios: one in which an OV intends to overtake the platoon. Such a system implies the last of the platoon's FVs to detect the OV. This may be achieved by vehicle-to-vehicle (V2V) communications, if OV is capable of it and has implemented the proper equipment compatible with the ones installed on the platoon's vehicles. However, if the OV does not have V2V capabilities, there is the need to also implement a vehicle detection system with the purpose of identifying the OVs that intend to overtake the platoon, and an information method for other traffic participants to let them know in what way the platoon may be overtaken.

The other scenario is the one in which an OV intends to exit the highway and the platoon is positioned in its path to the exit lane. Such a system implies V2V communication system implemented on all the vehicles because the OV trying to exit must inform the platoon about its intentions. But to implement such a system is mandatory to have knowledge about the exact position of the OV, in order to determine the position in the platoon where the gap should be formed. Location is usually found via global positioning systems, such as GPS or GLONASS. All these systems, however, involve a location precision error, that may be up to several meters. Modern GPS receivers can now deliver high accuracies (centimeter level) with the help of real time kinematic navigation or differential GPS, both depending on the existence of ground-based reference stations. In cities, additional information may be added to the positioning system from the GSM network, via A-GPS (assisted GPS). This increases location precision and reduces error to several centimeters. But outside the cities, where there are only few GSM antennas and GPS ground stations are not always available, precision cannot be as good. This may lead to malfunction of the whole dynamic platoon concept, as there is not a certainty that the gap produced to allow the vehicle to go through the platoon to exit the highway is properly placed.

Therefore, in order to achieve a good functionality of the whole system, it is necessary to implement some additional fixed detection points located certain distance ahead of the exit points that will locate with great precision both the exiting vehicle and all the trucks in the platoon. Then, by sending the information to the platoon, the trucks may decide with proper knowledge what the gap position should be.

In both scenarios, when the gap between vehicles is formed, the platoon is split in two. Considering the platoon concept, there is a safety concern if the platoon would be considered intact when an outside vehicle is integrated in it. This happens because the FV's assume that, in case of an emergency, they would receive the necessary information (like braking) in due time from the LV. If the distance between platoon vehicles became too big (in case of a gap formation) the information may arrive late at the vehicles behind the gap. Also, the uncertainty induced by the behavior of the external vehicle is a safety risk.

There is also the case that must be foreseen in which an additional external vehicle fills in the gap formed, hence having two vehicles intruding in the platoon, instead of only one. It is important in this case for the vehicles in the gap area to figure out when the external vehicles have left the platoon in order to get close together again. If all the vehicles are still considered as a single platoon it is very difficult to detect when the intruders have left, especially considering that OVs may not have V2V capabilities. Also, if OVs reduce their speed, there may be a communication problem for the maintenance of the platoon, due to a possible distance between platoon vehicles bigger than the maximum reliable V2V communication distance.

Based on all the above considerations, we have concluded that the proper solution is to temporary form two separated platoons, meaning that the FV behind the gap become the LV of the new second platoon. When the OV leaves the gap the two platoons may reunite as one.

In Figure 1 the stages of overtaking the platoon are shown:

- OV intends to overtake the platoon and is detected.
- OV overtakes the last two vehicles, splitting the platoon in two.

- OV overtakes the next two vehicles; the initial LV is no longer part of the platoon.
- The initial platoon is reformed.

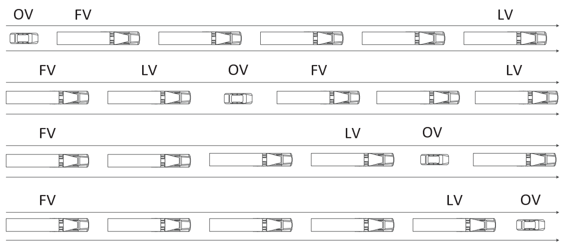

Figure 1: OV overtaking a platoon.

It is obvious that, in this case, it's not possible to have a LV with human driver and for all the other ones the autonomous system to have full control. As any FV may become a LV (at least temporary), it is important to implement a driver alert system, that will inform a FV's driver about the transformation to LV.

2.2 System Requirements

Considering the above system description, the following elements must be included in order to obtain the desired functionality (Kavathekar, 2012; SARTRE-Consortium, 2012):

- For longitudinal control, when the vehicle in front is part of the platoon, V2V communication will be used to exchange performance parameters (speed, braking, acceleration, detected obstacles, steering, etc.) between LV and FV's. To maintain a certain distance between platoon members on board systems like Adaptive Cruise Control (ACC), that automatically adjusts the vehicle speed to maintain a specified distance from the vehicle in front, or Collision Avoidance Systems (CAS) will be used.
- For longitudinal control, when the vehicle in front is not part of the platoon (for example an OV that enters in the middle of the platoon), the FV decelerates to increase the gap to the OV in order to provide a larger safety margin, by using on board systems like ACC or CAS.
- Lateral control can be achieved by using on board systems. Lane departure keeping systems are used to ensure that the vehicle remains in its lane. Magnetic markers or reflective guardrails can be installed in the road infrastructure also to be detected by on board systems.
- Identification of vehicles requiring a gap may be done using V2V communications, if OV have such a system implemented, or it will be done using video cameras to detect an overtaking vehicle that requires a gap.
- Information system is necessary to inform other vehicles that do not have V2V implemented about their permissions related to the platoon's movement. Each truck forming the platoon should have a VMS (variable message sign) or LCD on their back to display information such as: "Overtaking not allowed", "Overtake one truck", "Overtake two trucks" or other information messages.
- Communication systems – detailed in the next chapter.

3 DYNAMIC PLATOONING CONCEPT

3.1 Communication Network Architecture

The communications that must be considered are (Vlastaras et al, 2014; Amoozadeh et al, 2015):

- For communication between vehicles in the platoon, with the purpose to maintain the platoon, dedicated short range communication technologies will be necessary, that must be very robust, with very short delay and with safety and security mechanisms implemented. Depending on the length of the platoon and the used technology one can choose a centralized or decentralized approach.

  The main consideration should be the message propagation time, to assure that an emergency command will be received in due time by all the vehicles in the platoon. This gives the main restriction to the platoon length.

  In addition, it is more reliable to have a single message sent from LV to all FVs than to have the message rebroadcast by every FV: any error in a FV will break or, worse, distort the message that will be sent to the rest of the platoon's vehicles.

- For communication between vehicles in the platoon, with the purpose to create/recreate the platoon, the same dedicated short range communication technologies will be necessary and also a Human-Machine Interface (HMI) for the driver to interact with the system.

- Identification of vehicles requiring a gap, if they have V2V communications implemented, will be done through wireless exchange of data between LV and OV, establishing a protocol for asking and receiving a gap in the platoon, based on OV's location.

- Infrastructure to vehicle (I2V) communications will be necessary for the second scenario, to accurately locate the OV that intends to exit the highway with the help of roadside beacons placed before the exits. The same dedicated short range communication technologies will be used.
- Global Navigation Positioning System that will provide vehicle location.

All these are presented in Figure 2.

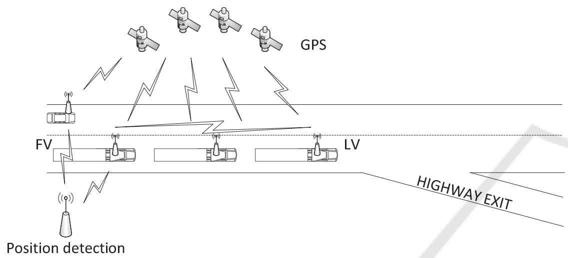

Figure 2: Example of communications for the platoon.

3.2 Platoon Formation Concepts

Platoons must have a unique ID that will allow the vehicles to identify at which platoon they adhere. This must be negotiated at the beginning of the platoon formation, when the first FV ask permission to join the LV. The ID should include the following elements:

- GPS coordinates of the place the first negotiation of the platoon took place.
- Direction of travel, considering geographical positions: N, NE, E, SE, S, SW, W, NW.
- Type of FV.
- A random number.

From all the above it results that the platoons will have different IDs so they will be easily identified. When an OV breaks the platoon in two, the second platoon will have a new ID, given by the above considerations. When a platoon arrives in the proximity of another platoon going the same direction (also the case when an OV broke the platoon and then left), the second LV must communicate with the first LV to negotiate a formation of a bigger platoon including all the vehicles.

4 CONSIDERATIONS REGARGING MINIMUM DISTANCE FOR ESTABLISHING COMMUNICATION

For the scenario in which an OV intends to exit the highway and the platoon is placed between it and the exit lane, the OV must inform the platoon and ask for a gap in it, using V2V communications. In this case, it is very important to see if there is enough distance available for the vehicle to follow all necessary steps and safely exit the highway.

The minimum distance (D) for establishing a communication with the platoon must be bigger than the minimum calculated distance (d) to the highway exit.

$$D > d \tag{1}$$

Minimum calculated distance is a sum of distances travelled by the vehicle and the length of the highway exit lane:

$$d = l_{el} + v_{pt} \cdot (t_{gap} + t_{in}) + d_{syn} + v_{ov} \cdot t_{COM} \tag{2}$$

where: l_{el} is the length of the highway exit lane (if one exists).
v_{pt} is the platoon's speed.
t_{rt} is the necessary time for the platoon to create the gap.
t_{in} is the necessary time for the vehicle to occupy the gap.
d_{syn} is the necessary distance for speed synchronization between the OV and the platoon.
v_{ov} is the OV's speed.
t_{COM} is the necessary time for exchanging messages.

The time needed for the vehicle to occupy the gap (t_{in}) include necessary time for signaling a lane change (t_{sig}) and the necessary time for performing the maneuver (t_{man}) without making sudden movements.

$$t_{in} = t_{sig} + t_{man} = t_{sig} + \frac{w_l}{v_{lat}} \tag{3}$$

where: w_l is the lane width.
v_{lat} is the lateral speed.

In order to provide enough space for the OV, the platoon must be split in two. The time required to separate the platoon (t_{bp}) depends on the length of the OV (l_{ov}), a safe distance (d_s) to leave between it and the trucks (both in front and behind the car) and the trucks braking acceleration (a_{brt}).

$$t_{bp} = \sqrt{\frac{2(l_{ov} + 2d_s)}{a_{brt}}} \tag{4}$$

The OV that is overtaking the platoon is supposed to have the right to travel at a superior speed, so, in order to execute the maneuver for splitting the platoon and exiting the highway, the OV must slow down and synchronize its speed with the platoon. The distance travelled by the OV from platoon split confirmation until it reaches the same speed is calculated as follows:

$$d_{syn} = \frac{v_{ov} \cdot v_{pt} + v_{pt}^2}{a_{brv}} \tag{5}$$

where: a_{brv} is the vehicle braking acceleration

In conclusion, the total necessary distance is:

$$D > d = v_{ov} \cdot t_{COM} + \frac{v_{ov} \cdot v_{pt} + v_{pt}^2}{a_{brv}} + v_{pt} \cdot \left(t_{sig} + \frac{w_l}{v_{lat}} + \sqrt{\frac{2(l_{ov} + 2d_s)}{a_{brt}}} \right) + l_{el} \tag{6}$$

As can be seen from (6), minimizing the distance and creating an efficient system will depend heavily on the necessary time for exchanging messages between the OV and the platoon, therefore choosing the right communication technology will be a very important step.

5 PROPOSED COMMUNICATION TECHNOLOGY

As the authors concluded in (Gheorghiu and Iordache, 2016) ZigBee protocol represents an alternative to Bluetooth and Wi-Fi communications for vehicular environments, being developed to ensure better energy consumption, even with the downside of lower data rates. Its main advantages are fast handshake connection (30 milliseconds), less interference from other 2.4GHz technologies (two of the ZigBee channels, 24 and 25, have less to no conflict with Wi-Fi and Bluetooth channels) and high equipment availability with accessible prices. DSRC technology, although developed especially for V2V communications, was not included in the comparison because of expensive equipment and low availability.

The ZigBee standard is built on IEEE 802.15.4 for packet-based wireless communication and enhances its functionality by providing flexible, extendable network topologies with integrated set-up and routing intelligence to facilitate easy installation and high resilience to failure. Usually it operates in the 2.4GHz band worldwide and uses offset quadrature phase-shift keying (OQPSK), that transmits two bits per symbol. The data rate varies widely, depending on the implementation, from 20 kbit/s to 250 kbit/s (ZigBee Alliance, 2016).

Related to road traffic communications, ZigBee has the advantage of being very flexible and allowing networks to be easily adjusted to changes by adding, removing or moving network nodes. The protocol is designed such that nodes can appear in and disappear from the network, making it very adaptable and proper for V2I communication. Another big advantage of a ZigBee network is that it can easily be installed and configured. The devices are also cheap, facilitating a large-scale implementation.

There are three methods to create a ZigBee network: pre-configured (all parameters are configured by the manufacturer), self-configuring (the network is set up by "discovery" messages sent between devices) and custom (adapted for specific applications/locations) (NXP Laboratories, 2014).

As ZigBee nodes are usually in sleep mode to achieve low power consumption, they need some time to wake up and respond, typically 15 milliseconds for a sleeping node to wake up, and another 15 milliseconds to access the channel. Compared to other wireless communications for short distances, such as Bluetooth or Wi-Fi, this latency time can be considered to be low.

The ZigBee protocol has many advantages from the connection time point of view, but the data rate available may not be enough for some applications. However, considering the details that will be formulated below, we shall be able to conclude that this technology presents enough advantages to be considered as a possible solution to the application that is presented in this paper.

ZigBee networks may co-exist with Bluetooth and Wi-Fi, as they incorporate listen-before-talk protocol and rigorous security measures. As presented in (Gheorghiu and Iordache, 2016) Wi-Fi interferences over ZigBee communications are the most important and most likely to occur in a road environment. As can be seen in Figure 3 and as was shown in the same paper, channel 26 is the most resilient to interferences caused by Wi-Fi communications, when it comes to handshake connection times, so the following tests will be based on these conclusions.

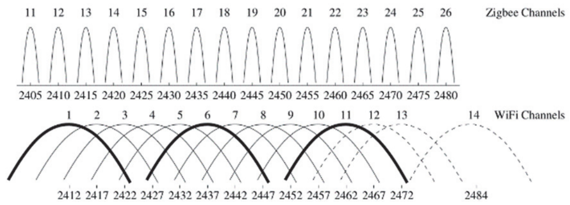

Figure 3: ZigBee and Wi-Fi Channels (Liang et al., 2010).

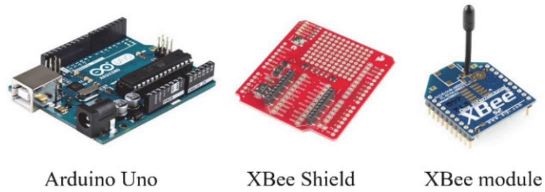

Figure 4: Hardware components.

6 MESSAGE EXCHANGE TIME MEASUREMENTS

In order to measure the necessary time for exchanging messages a typical message set structure has to be defined, based on the information needed by the system. Two messages are defined, one for the request sent from the OV to the platoon, and one for the response sent from the platoon to the OV.

Proposed request message contains 152 bits and, based on our calculations from chapter IV, includes the following information:

- Vehicle ID (random): 64 bits.
- Type of request: 8 bits.
- GPS position of the OV: 32 bits.
- Speed of the OV: 8 bits.
- Length of the OV: 8 bits.
- GPS position of the highway exit (if this is the case): 32 bits.

Proposed response message contains 32 bits and include the following information:

- Acceptance or rejection of the request: 16 bits.
- Number of the truck in front of which a gap will be created: 8 bits.
- Recommended speed for the OV: 8 bits.

Based on the OV's request, the last FV of the platoon will determine if the distance between the platoon and the highway exit is sufficient for a successful platoon separation, integration and exit of the OV. If there is not enough space, the request will be rejected and the vehicle will be informed to wait for the highway exit behind the platoon.

In the following, is presented an analysis of the time needed for transmitting successful messages between OV and LV/FV, performed in the laboratory, using the following hardware: one router and four XBee S2 modules, each connected to an Arduino Uno board with an XBee Shield (Figure 4).

The authors chose to use these ZigBee implementation modules because of their reasonable price and high availability in many countries.

An XBee 2mW Wire Antenna - Series 2 was used for these tests, having the following main technical characteristics: 3.3V @ 40mA needed power supply, 250kbps Max data rate, 2mW output (+3dBm), 120m range. Two pairs of transceivers were created, each of them with one of the XBee modules set as Coordinator – XB_C and the other as End Device – XB_{ED}. Every pair was configured using the parameters presented in Table 1.

Table 1: XBee Coordinator and End Device configuration.

Modified parameters	Coordinator settings (pair 1)	End device settings (pair 1)	Coordinator settings (pair 2)	End device settings (pair 2)
PAN ID	11	11	10	10
DH	13A200	13A200	13A200	13A200
DL	40E778BF	40E7795C	40E922BF	40E922BD
BD	57600	57600	57600	57600

PAN ID (Personal Area Network ID) identifies the network that the device will join. This parameter was set differently for every pair of transceivers, to avoid unwanted connections between the four modules and joining other possible existing networks.

DH represents the upper 32 bits and DL is the lower 32 bits of the 64-bit destination extended address. Each device in one pair was configured with DH and DL of the other device, so they will communicate with each other.

BD represents the Baud Rate, and it was chosen a value sufficient for transmitting necessary data.

The tests focused on measuring the time needed for a complete exchange of messages (one request and one response) between two XBee modules, one that should be on board of the OV, and the other on board of the LV/FV. Messages have been formed as described earlier in this paper.

Three scenarios were considered:

- Message exchange with random Wi-Fi interference (considering that it is not possible to know very precise what communications will occur during the exchange of messages in the ZigBee network).

- Message exchange with a wireless router set on the Wi-Fi channel closest to the tested ZigBee channel, and a large file transfer in progress during this phase of the tests.
- Message exchange with another pair of XBee modules set on the same communication channel as the ones used for measurements, and transmitting data with a high rate.

As stated in previous chapter, the authors chose to measure and compare message exchange times for 2 of the 16 ZigBee channels, channel 12 that is clearly overlapping with Wi-Fi channel 1, and it will certainly be affected by a heavily data transfer, and ZigBee channel 26, whose frequency band is less likely to be occupied by a data transfer on Wi-Fi channel 13.

Five tests were performed:

- Message exchange on ZigBee channel 12 (0x0C), with random Wi-Fi communications.
- Message exchange on ZigBee channel 12 (0x0C), with Wi-Fi communications set on channel 1.
- Message exchange on ZigBee channel 26 (0x1A), with random Wi-Fi communications.
- Message exchange on ZigBee channel 26 (0x1A), with Wi-Fi communications set on channel 13.
- Message exchange on ZigBee channel 26 (0x1A), with another ZigBee communication active on the same channel.

A number of 100 measurements were performed for each test. Median values for the message exchange time can be seen in Table 2 and all values can be seen by comparison in Figure 5 and Figure 6, based on used ZigBee channel.

Table 2: Median values obtained in tests (milliseconds).

ZigBee channel	Normal Conditions	Wi-Fi channel 1 active	Wi-Fi channel 13 active	Another ZigBee channel 26 active
12	38	499	-	-
26	37	-	78	50

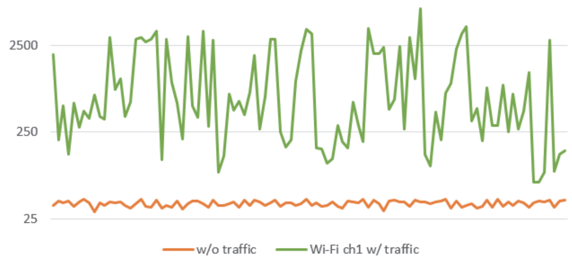

Figure 5: Message exchange time (ms), ZigBee channel 12.

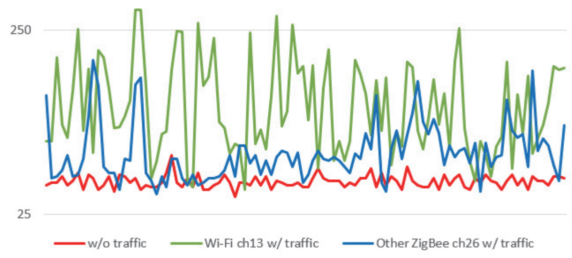

Figure 6: Message exchange time (ms), ZigBee channel 26.

The charts presented above leads us to the following conclusions:

For ZigBee channel 12, that overlaps Wi-Fi channel 1, it results a distinguishable difference between the case with no traffic and the scenario with Wi-Fi traffic on channel 1. Considering a speed difference between OV and the last FV of the platoon of 8.5m/s (about 30.6 km/h – with a platoon traveling at 100 km/h and the OV's speed of 130 km/h), and a communication distance of 50m (25m before OV reaches FV and 25m after it overtakes FV – a moderate value, considering that, in theory, ZigBee communications reach 70m in open field => 140m total distance) results a total communication time of 50/8.5 = 5.88 seconds. Therefore, a total transfer time of 4.098 seconds (maximum obtained in tests) may still be proper for the requirement/acknowledge communication.

For ZigBee channel 26, the situation is even better, as in our tests the maximum requirement/acknowledge communication time was 365 milliseconds and, consequently, this represents a proper OV-FV communication solution.

7 CONCLUSIONS

As the result of the tests performed, we may conclude that ZigBee seems to be a proper solution for V2V communications between OV and FV, providing enough time for data exchange (considering that the message's length is reduced), as the speed difference between OV and the platoon is not very high.

The tests have been made in all the possible scenarios: lowest, random and highest Wi-Fi interference, and the values obtained proved to be enough to ensure the proper OV-FV communication.

The next steps will refer to modelling in detail the communication network that will reliably deliver messages needed to guide the platoon and to support the right assistance in interaction with the other vehicles. Laboratory measurements with more aggressive electromagnetic noise are foreseen. Also measurements in a real vehicular environment will be performed to validate the laboratory tests.

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