LTE4V2X - impact of high mobility in highway scenarios

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***Abstract*—In the near future, most new vehicles will be equipped with short-range radios capable to communicate with other vehicles or with roadside infrastructure. These new networks known as vehicular networks are seen to be one of the most valuable concept for improving road safety and transport efficiency, and as a key technology enabling the provisioning of value-added services to passengers and drivers. Vehicular networks raise a number of unique challenges due to the extremely dynamic network topology and the highly variable number of mobile nodes. To overcome these problems, an effective solution is to organize the network in a way which will facilitate the management tasks and permit to deploy a wide panoply of applications such as urban sensing applications. In a recent work [1], we proposed LTE4V2X, a novel framework for a centralized vehicular network organization using LTE. In the continuity to this work, this paper presents new performances evaluation of LTE4V2X in highway scenarios in order to evaluate the impact of high mobility. We studied its performances against a decentralized organization protocol and All-LTE protocol for a well known urban sensing application, Floating Car Data (FCD) application. We analyze the performances of LTE4V2X using NS-3 simulation environment and a realistic highway mobility model. We also analyze analytically the impact of the handover on the performances. The results show that LTE4V2X can handle efficiently high vehicles' velocities and leads to performance improvement by lowering the overhead induced by control messages, reducing the FCD packet losses, as well as enhancing LTE bandwidth usage.**

***Index Terms*—Vehicular networks, organization, self-organization, clustering, LTE, WAVE, 802.11p, centralization, Floating Car Data, high mobility, handover.**

I. Introduction

In recent years, vehicular networks have attracted a considerable attention from the research community and the automotive industry aiming to provide not only safety and efficiency in the transportation systems but also leisure and infotainment to the driver and the passengers. However, these networks are challenging as they have some specific characteristics, such as high velocity of vehicles and the dynamic network topology, that need to be taken into account in designing any solution for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. A lot of works propose solutions to handle some of these issues [2] [3] [4]. Most of them are based on the creation, in a decentralized way, of dynamic clusters to self-organize a non-heterogeneous 802.11p vehicular network. With a highly dynamic environment such as vehicular networks, a decentralized clustering is not appropriate since it creates a large amount of overhead within the network.

In [1], we proposed LTE4V2X, a novel framework for the organization of vehicular networks using the existing LTE network. LTE4V2X uses a centralized clustering mechanism: eNodeBs organize vehicles into clusters, and broadcasts the clusters topology to the vehicles. Performances evaluations were carried out for urban topologies with a well known urban sensing application, the FCD application. Floating car data (FCD) are based on the collection of localization, speed, direction of travel (heading) and time information from vehicles in order to feed a traffic management server. Based on these data, traffic congestion can be identified, travel times can be calculated, and traffic reports can be rapidly generated. In contrast to traffic cameras, license plate recognition systems, and sensor loops embedded in the roadway, no additional hardware on the road network is necessary for FCD application to work. The FCD version used in this architecture is Decentralized Floating Car Data (DFCD), which means that each vehicle generates its own data (it retrieves its position, velocity and heading) before transmitting it through the network. In this paper, we carried out new extensive performance evaluations of LTE4V2X in inter-urban topologies characterized by large LTE cells and high vehicles' velocities. We also analyze the delay induced when a vehicle execute a handover from an eNodeB (original) to an adjacent one (destination). In fact, we calculated the time between the time when the moving vehicle sends the last FCD frame to the original eNodeB and the time when it executes a handover and sends the first FCD frame to the destination eNodeB. This document is structured in five parts. In section 2, a summary of background knowledge and related work are presented. After a presentation of LTE4V2X in Section 3, a presentation and analysis of simulations study is given in Section 4. Section 5 presents a short analytical study of the delay induced by a handover, and Section 6 concludes the paper and discusses some directions of our future research.

II. Background and Related Work

Network self-organization is a widely covered topic in the domain of wireless ad-hoc and sensor networks, and particularly in vehicular networks. In fact, vehicular Ad-hoc Networks have some own characteristics, especially high mobility, that have important implications for designing solutions. To deal with some of the induced challenges, a self-organizing architecture can be set up to simplify the network management task and to permit the deployment of a lot of services. In this section, we will first outline the advantages of vehicular networks self-organization and determine the services that could take advantage of such self-organization architecture. Second, we will evoke some recent related works.

A. Background

Self-organization architecture should take advantage of node properties to issue a global virtual structure enabling the network self-organization, and it should be sufficiently autonomous and dynamic to deal with any local change. Self-organizing mechanisms uses the notion of clustering and virtual backbone. The clustering approach consists in the partition of the network in homogeneous zones named clusters. Each cluster has at least one cluster head (CH) and a set of members. Generally, the members of one cluster have some common characteristics as contiguous velocities or coordinates, etc. The clustering structure is usually used as a support of a backbone structure. The virtual backbone is constituted of the cluster heads, and creates a robust set of best interconnected nodes.

Clustering approach is well suited for vehicular networks, and vehicular urban sensing applications particularly. Indeed, the vehicles have constrained mobility patterns due to the road structure, and thus tend to be naturally grouped into clusters. Moreover, the applications used in vehicular networks are often tied to the geographical position, and the messages need to be disseminated or collected in a given region (e.g. a cluster). This is the case for FCD (Floating Car Data) application, as well as any kind of urban sensing application which collects data from sensors embedded within vehicles.

There are two main types of self-organization: (i) decentralized organization, in which the ad-hoc network is autonomous and does not use any external infrastructure to organize itself, and (ii) centralized organization, in which the organization of the ad-hoc network is delegated to a third-party fixed infrastructure (e.g. eNodeB). Typically, in the case of vehicular networks, existing works often used a decentralized organization. However, vehicular networks often co-exist with a fixed infrastructure (e.g. Road-side unit, Base station, eNodeB). This is the reason why our framework LTE4V2X investigated a centralized self-organization mechanism, using the LTE network as the fixed infrastructure in charge of the network organization task.

B. Related Work

High mobility is a main issue in vehicular networks. Vehicles mobility leads to connectivity failures and complex mobility management mechanisms. Recent works [5], [6], [7], [8], and [4] show how VANET community is concerned about this aspect. Indeed, as one of the main purpose of VANETs is to provide road safety mechanisms, the wireless communications have to be designed in order to be as dependable and safe as possible.

In [5], the authors study the impact of vehicles mobility on VANET connectivity. They perform advanced analytical study for highway scenarios, and give a mean to predict the network 1-connectivity, i.e. the probability to have the capability for any vehicle to communicate with any other vehicle via multi-hop routing. They introduce a speed parameter, the *equivalent speed*. This parameter, depending on the average vehicles speed and standard deviation of the vehicles speed, has the particularity to create a relation between vehicles mobility and VANET connectivity: when the equivalent speed decreases, the VANET connectivity increases. Then, the authors prove that (i) the connectivity decreases when the average speed increases (ii) the connectivity increases when the standard deviation of the vehicles speed increases.

[6] presents a model for the connectivity duration in a VANET and the size of each cluster formed by a set of communicating vehicles on a highway (considering multi-hop communications). Their results are useful for designing multi-hop VANET applications: they give, among other information, how long the relay chains are established in a highway, or the packet loss against the distance between source and destination. For instance, they show that packet loss rate remains below 1% when the distance is below 250m (we have only single-hop communications), then increases linearly until 500m. Beyond 500m, packet loss is still linear, but multi-hop communications slow down the packet loss increase. The authors also developed a model which allows to determine the probability density function (PDF) of the connectivity period duration on highways.

In [7], the authors propose a clustering algorithm for an heterogenous network composed of a vehicular network and a cellular network. In their proposed architecture, cellular network is used to upload data from vehicles, but also has indirect effect on cluster formation: the headings of the vehicles in relation to the eNodeB is taken into consideration in their cluster formation algorithm, even if their clustering mechanism is decentralized. Using NS-2 simulation, they studied the impact of vehicles velocity variance on different VANET routing protocols. Simulation results showed that their protocol really improves the routing in the VANET (it lowers the overhead and packet loss). This proves that cellular networks can significantly improve vehicular networks performances. However, the overhead induced by their protocol remains close to the other classic VANET routing protocols, and the packet loss needs also to be more reduced.

LTE4V2X, the framework proposed in this paper, is made to efficiently collect and aggregate data from a vehicular network, using LTE network. We particularly analyze the impact of high mobility on LTE4V2X for different highway topology scenarios.

III. LTE4V2X

In this section we will briefly present the architecture and the different mechanisms involved in LTE4V2X framework.

A. Architecture

As stated before, our framework LTE4V2X investigated a centralized self-organization mechanism, using the LTE network as the fixed infrastructure in charge of the vehicular network organization task (i.e. clusters management).

We consider that all vehicles have both LTE and 802.11p interfaces. As indicated before, we demonstrate the efficiency of our framework for a well known urban sensing application, FCD application. However, the self-organization architecture of LTE4V2X can be extended to any application based on data collection and/or dissemination.

The size of a cluster is at most the range of 802.11p, so that each node can reach the other nodes of the cluster (the CH more particularly). Each vehicle sends FCD data periodically and each eNodeB manages the vehicles that are under its coverage area. In each cluster, a cluster head (CH) is elected (see Figure 1. The CH has the responsibility to send application data of itself and its cluster members to the eNodeB via LTE. Cluster members only send their application data via 802.11p to their CH.

All nodes (i.e. vehicles) can be elected as CH. CHs aggregate data of cluster members before sending it to the eNodeB. This will lower LTE goodput by avoiding to send useless data (e.g. when the heading and velocity of a vehicle is unchanged, CH can avoid to send data of this node to the eNodeB). The CH can also use a compression algorithm on the aggregated data to save more bandwidth.

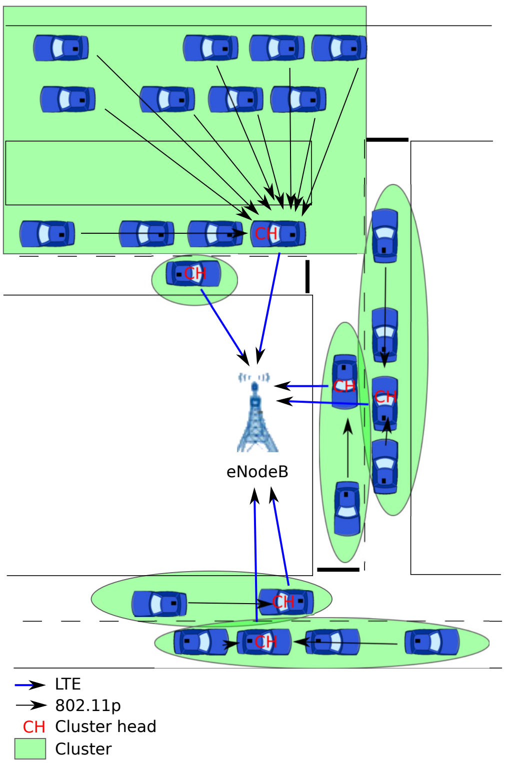

Figure 1. LTE4V2X architecture

B. Protocol description

The systems runs an "**Initialization phase**" when it starts. Then, it runs in a cyclic manner (see Figure 2): each round contains three phases and is repeated indefinitely. The three round phases are: (i) **Setup phase**, in which the eNodeB creates and updates clusters (ii) **ADV (Advertisement) phase**, in which CHs send a notification frame in the VANET, and (iii) **Collection and aggregation phase**, in which cluster members send their FCD to CHs, and CHs send aggregated FCD to the eNodeB. Note that nodes use TDMA in each cluster to send their FCD (position, velocity and heading) to the CH.

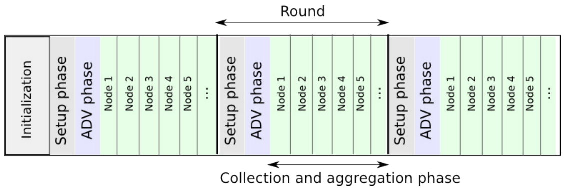

Figure 2. Round phases

1) Initialization Phase: During the initialization phase, the eNodeB receives FCD directly from all vehicles. This phase is executed only one time, when the network starts, and allows the eNodeB to know vehicles positions and then to create coherent clusters. At the beginning, the vehicular network is not organized and there is no clusters created. All the vehicles send an ID request using an ID frame, until they receive an ID from the eNodeB. After that, the nodes send their FCD (position, speed and heading) to the eNodeB, using the same mechanism as if they were entering the network (see section Arrival of New Nodes). At the end of this phase, the eNodeB runs an algorithm to organize the vehicular network and form the clusters (see section Periodic Operations). After that, the eNodeB broadcasts this organization using a frame that defines the cluster heads and their associated cluster members.

The ID request frame is used to add a new IPv6/ID association, to delete an existing association or to ask for the IPv6 address corresponding to a given ID.

2) Maintenance: In this Section, we detail how LTE4V2X maintains the clusters using the eNodeB: how the eNodeB manages the arrival and departure of nodes, and what periodic checks and control messages are sent by the eNodeB.

a) Arrival of New Nodes: The arrival of a new node in a cluster is quite simple: First, the new node waits for the reception of an ADV frame in the VANET, a "Cluster update" frame from the eNodeB, or when a timeout counter expires. The reception of this frame allows the new node to know when the Collection and Aggregation phase will be initiated. During the next Collection and Aggregation phase, the new node sends an FCD frame directly to the eNodeB, like in the Initialization phase (with 0x0000 as Cluster ID). After that, the eNodeB will integrate the new node in the next "Cluster Update" frame.

b) Leaving Nodes: The behavior will obviously be different if the leaving node is a CH or if it is a simple member node.

When the leaving node is a member node, it is detected at most a round duration after its disconnection, because the eNodeB can easily notice when it did not received FCD data from it. The leaving node will be removed from the clusters when the eNodeB does not receive FCD for a given number of consecutive seconds.

When the leaving node is a cluster head, the process is different. If the leaving CH node leaves before sending the aggregated FCD, all the cluster FCD will be lost for this round. The eNodeB will also notice this loss and fix the cluster for the next round.

c) Periodic Operations: A periodic check is executed by the eNodeB each round in the Setup phase.

The eNodeB tries to create clusters which have a lifetime as long as possible. The size of a cluster is at most the range of 802.11p, so that each node can reach the other nodes of the cluster (the CH more particularly). eNodeB creates clusters which contains the largest number of nodes circulating in the same direction (see Figure 1). This algorithm is executed periodically by the eNodeB during the Setup phase.

If the calculated clusters are different from the current ones, the eNodeB broadcasts a "Cluster Update" frame. The "Cluster Update" frame contains commands for each cluster that needs an update. The commands can notify the addition of a node, the removal of a node, the ID a the new CH of a cluster, or the new ID of a cluster.

In the ADV phase, the clusters configuration is spread in the VANET: each CH broadcasts a short frame which contains the next CH ID of its cluster and the number of cluster members. Indeed, the CH can take the initiative of choosing an other node as CH. This frame also allows the cluster members to know that their CH is still alive.

d) Collection and Aggregation Phase: During this phase, each node sends its FCD (position, speed and heading) to its CH, in the attributed time slot. The time slots correspond to the order used by eNodeB in the last update frame. If the node does not know the IPv6 address associated with its CH ID, it sends an ID request frame (see section Initialization Phase).

Just before the end of this phase, each CH sends the aggregated data (which may be compressed) to the eNodeB. The size of this frame depends on the compression algorithm, the aggregation process, and obviously the number of nodes in the cluster. For example, with 30 nodes in the cluster and the compression algorithm used in tar-gzip format, the frame size reaches about 128 bytes.

IV. Simulations

A. Simulation Assumptions

This section presents the parameters and metrics used in the simulations. The topology used in our simulations is represented in Figure 3: two parallel highways (2x3 lanes) cross the area, and a eNodeB is placed in the middle.

We implemented our protocol using `NS-3.10` (Network Simulator) [9], and generated vehicles mobility using `VanetMobiSim` [10].

We compared our protocol against a decentralized clustering protocol (DCP). In this protocol, the vehicles compute the clusters each seconds, and send an ADV (Advertisement) frame if they are cluster heads (CH). Then, all non-CH nodes send their FCD to their CH. After that, the CH sends the aggregated data to the eNodeB.

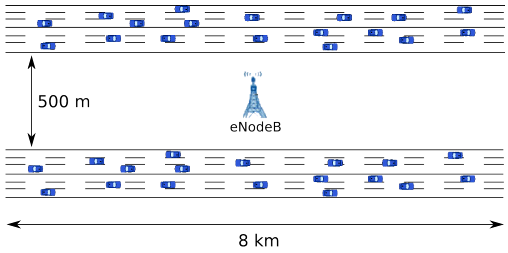

Figure 3. Simulation area

The performance metrics used to evaluate the simulation results were:

- **Efficiency**: This is a metric we introduced to reflect the ability for the protocol to optimize the LTE bandwidth and to have reliable inter-vehicle communications. It is given by the formula: $E = \text{Number of vehicles per cluster} \cdot (1 - \text{FCD loss rate})$. Indeed, when a cluster contains a lot of vehicles, it aggregates many FCD in a single frame, and thus compress and aggregates more efficiently, resulting in an optimization of the LTE bandwidth. Moreover, a high FCD loss rate implies non-reliable inter-vehicles communication (mainly due to non-efficient clustering mechanism). For this metric, we took also in consideration "All-LTE", as a reference for LTE4V2X and DCP. "All-LTE" is a very simple protocol in which all vehicles send their FCD directly to the eNodeB (i.e. no clustering mechanism)
- **Overhead**: This reflects all non-useful bytes exchanged in the network, i.e. control messages (ID, ADV, "Cluster update" and "Cluster topology" frames)
- **Packet loss**: This is the percentage of FCD that are sent by a vehicle but never received by the eNodeB

The simulation area, the simulation time, the 802.11p maximum range and the iteration number for each simulation case were common to all simulations (see Table I). These parameters were also used for urban topologies in [1], except for the simulation area, which was 1 km^2 (to match urban eNodeB coverage area).

Parameter	Value
Simulation area	$8km^2$
Simulation time	120s
802.11p maximum range	300m
Iteration number for each simulation case	10

Table I
Global simulation parameters

In order to analyze the performance metrics evolution with different vehicles' densities, we chose the parameters presented in Table II. These parameters were chosen to be as most realistic as possible. We chose the IDM mobility model, with lane changing feature. In [1], we presented results for simulations that were done with the same parameters (except the velocity), for urban topologies.

Parameter	Value
Vehicles number	100 to 300, step 50
Vehicles velocity	100-145 km/h
Mobility model	IDM Lane Change (with `VanetMobiSim`)

Table II
VEHICLES NUMBER VARIATION PARAMETERS

In order to analyze the performance metrics evolution with different vehicles' velocities, we chose the parameters presented in Table III. All vehicles are moving at the same speed for a given simulation case, using the "constant speed motion" model of `VanetMobiSim`. This does not reflect real vehicles movement, but it ensure to actually see the impact of vehicles' velocity.

Parameter	Value
Vehicles velocity	90 to 145 km/h, step 18 km/h
Vehicles number	300
Mobility model	Constant speed motion

Table III
VEHICLES VELOCITY VARIATION PARAMETERS

B. Simulation Results and Analysis

This section presents and analyze the results we obtained during our simulations. First, we will analyze the metrics evolution when the vehicles density varies. Second, we will analyze the performance metrics evolution when varying vehicles' velocities.

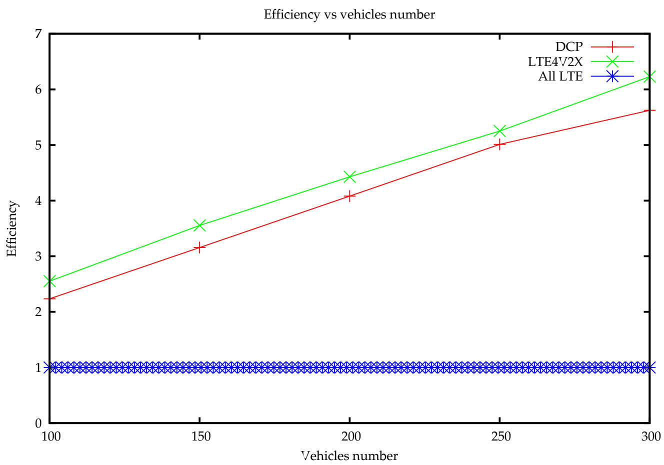

Figure 4. Efficiency vs Vehicles number

1) Vehicles' density variation: Figure 4 shows the efficiency of three protocols, in terms of LTE bandwidth usage and FCD packet losses. The three compared protocols are LTE4V2X, DCP and "All-LTE", in which all nodes send directly their FCD to the eNodeB. It is interesting to point out that LTE4V2X is above DCP and All-LTE, denoting that LTE4V2X combines an optimization of the LTE bandwidth and a clustering mechanism which allows a low FCD loss in the VANET. Moreover, its efficiency increases with the vehicles number, because the LTE bandwidth is more optimized when we aggregate a lot of FCD in a single frame, and the size of the aggregated FCD frames increases with the vehicles density. On the contrary, All-LTE have a very low and constant efficiency, because it does not try to optimize the LTE bandwidth at all.

Figure 5 shows the overhead of the two protocols in the LTE and VANET networks. We can observe on this figure that LTE4V2X overhead remains very low in the VANET, while its

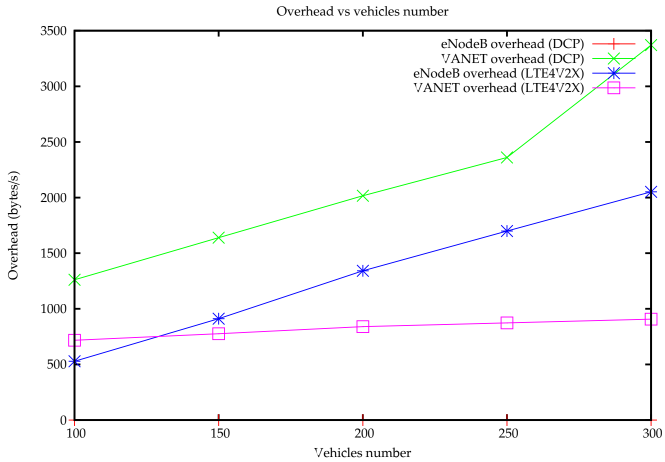

Figure 5. Overhead vs Vehicles number

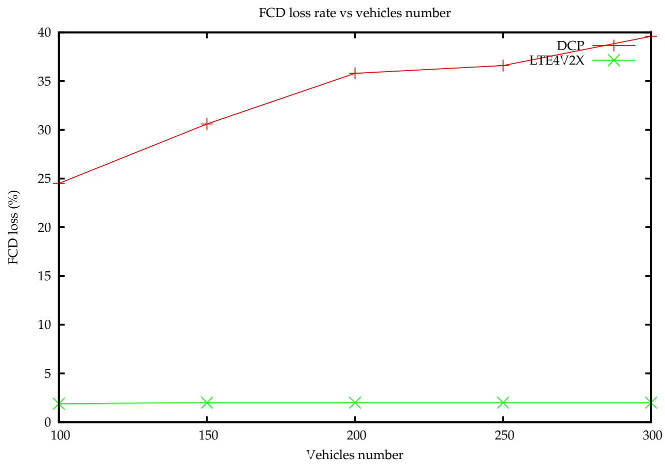

Figure 6. FCD packet loss vs Vehicles number

overhead in the LTE network is increasing linearly with the vehicles number, in parallel to the DCP overhead in the VANET. As DCP is decentralized, there is no management packet exchanged in LTE network, so all its generated overhead is contained in the VANET, whereas LTE4V2X transposes a part of the overhead from the vehicular network to the LTE network, since the clusters are managed by the eNodeB.

Figure 6 shows the FCD loss for the two protocols. It is interesting to point out that DCP packet loss increases with the vehicles number, whereas LTE4V2X packet loss remains the same (∼2%). This can be explained by the fact that the packet loss is only induced by the wireless channel, and does not depend on the clustering mechanism or protocol. Moreover, its centralized approach allows it to have a good overview of the VANET, and thus create better clusters and loose very few packets. Indeed, DCP can send FCD to non-existing or non-reachable cluster, as it has only a local view of the network.

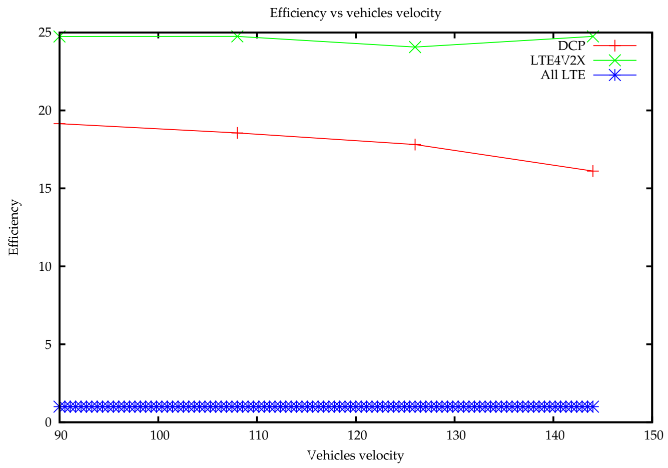

Figure 7. Efficiency vs Vehicles velocity

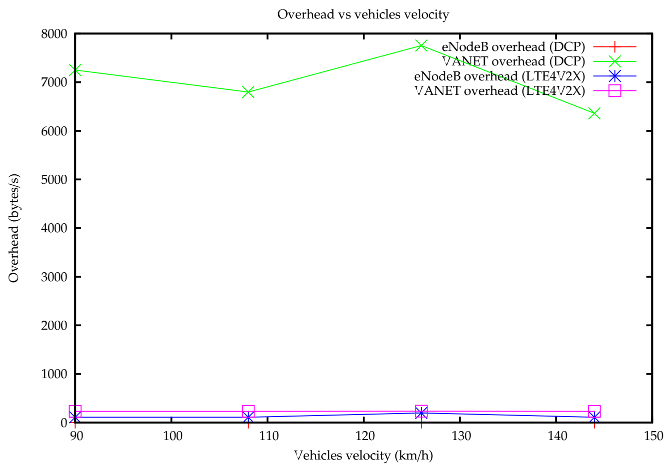

Figure 8. Overhead vs Vehicles velocity

2) Vehicles' velocity variation: Figure 7 shows the efficiency in terms of LTE bandwidth usage and FCD packet losses. The three compared protocols are LTE4V2X, DCP and "All-LTE", in which all nodes send directly their FCD to the eNodeB. Like Figure 4, this figure shows that LTE4V2X is the most efficient. Its efficiency is almost constant, whereas DCP efficiency decreases when the vehicles velocity increases. This enlighten the fact, as predicted, that DCP does not good support high mobility, due to its decentralized approach which induces non-efficient management of incoming and leaving nodes.

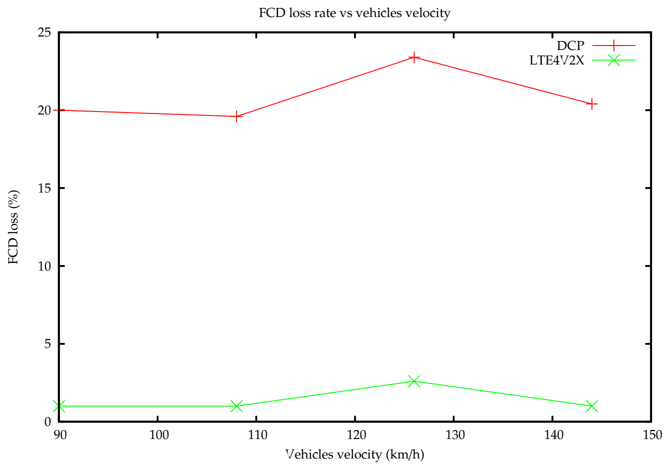

Figure 9. FCD packet loss vs Vehicles velocity

Figure 8 presents the overheads on the VANET and LTE networks, for LTE4V2X and DCP. It clearly outlines that DCP induces a high overhead in the VANET. The centralized approach of LTE4V2X allows it to lower the total overhead, and spread it in the LTE and VANET networks.

Figure 9 shows a nearly constant FCD loss for both LTE4V2X and DCP: LTE4V2X remains around 1-2%, whereas DCP remains around 20-23%. For the same reasons as in the previous section, DCP has a higher packet loss, because of its decentralized clustering mechanism. The vehicles velocity does not impact the packet loss, as all vehicles have the same speed. Then, the relative velocity between vehicles is null, and the wireless channel is not degraded.

V. Analyzing the Impact of Handover

In this section, we evaluate the impact of the handover on LTE4V2X: as the FCD application is periodic, we evaluated the delay between two FCD frames when there is a handover of the vehicle from an eNodeB to an adjacent one. We calculated and compared this delay for the two protocols: LTE4V2X and DCP. When a vehicle arrives into a new cell, the waiting time before the first FCD transmission depends exclusively on the moment the vehicle arrived in the round of its new eNodeB, as the two following sections will show. We do not consider the LTE handover delay, as it is the same for the two protocols.

A. Impact of the handover in LTE4V2X protocol

When the vehicle is connected to its new eNodeB, it has to wait for an Update frame, and then a given time, depending on its attributed ID, in order to avoid simultaneous communications when vehicles arrive at the same time. We identified the worst and best cases, and deducted the time between the handover of a vehicle and its first FCD transmission to the destination eNodeB (see Equation 1, where t is the arrival time of the vehicle and t=0 refers to the end of the setup phase). t_1 is a constant gap inserted by the CH between the reception of the “Cluster Update” frame and the sending of the ADV frame. t_2 is a constant gap between each FCD transmission by the cluster members.

$$\begin{aligned} f(t) = \;& \texttt{Round duration} + t_1 + t_2 \cdot \texttt{ID} - t \\ & \text{where} \quad 0 \leq t < \texttt{Round duration} \end{aligned} \quad (1)$$

B. Impact of the handover in DCP protocol

The vehicle waits a randomly computed time (between 0 second and a round duration) before sending its first FCD frame in the VANET, in order to avoid simultaneous FCD sending when several vehicles arrive at the same time. We took in consideration the worst and best cases, and deducted the time between the handover of a vehicle and its first FCD transmission to the destination eNodeB (see Equation 2 where t is the arrival time of the vehicle and t=0 refers to the end of the setup phase).

$$\begin{aligned} g(t) \;=\; & \texttt{Round duration} \\ & + 2 \cdot \texttt{Setup phase duration} \\ & + \texttt{a time depending on CH ID} - t \\ & \text{where} \quad 0 \leq t < \texttt{Round duration} \end{aligned} \quad (2)$$

C. Results analysis

If we apply this function to a round duration of 1s, a setup phase duration of 0.5 s, a mean ID of 200 (i.e. 400 vehicles), $t_1 = 1ms$, and $t_2 = 1ms$ (which allows to have up to 400 FCD transmitted in each cluster in one round), we obtain for LTE4V2X and DCP a mean time of respectively **0.7 seconds** and **2.202 seconds** before a node transmits its first FCD in the new eNodeB. Then, if we assume that the vehicle transmitted it last FCD to its previous eNodeB an average of a half round duration (0.5 seconds), the mean time between two FCD frames when we have a handover is respectively **1.200 seconds** and **2.702 seconds**.

Figure 10 shows, for LTE4V2X and DCP, the time between the reception of the last FCD frame by the source eNodeB and the reception of the first FCD frame by the destination eNodeB, depending on the time when the vehicles arrives in the new cell, in reference to the end of the setup phase. It was plotted using Equations 1 and 2, with an offset of a half round to reflect the time between the last FCD frame received by the source eNodeB and the actual handover. We observe that DCP always induces more delay than LTE4V2X.

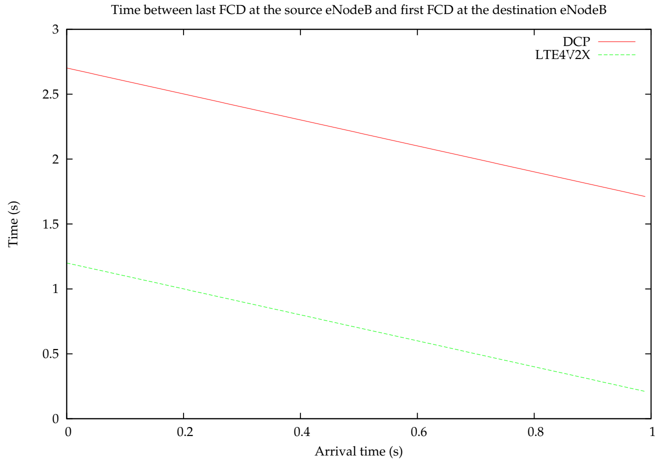

Figure 10. Handover time

VI. Conclusion

This paper presented LTE4V2X, a novel framework which uses the eNodeBs of the LTE network to self-organize the vehicular ad-hoc network. This framework was compared to a decentralized (DCP) and All-LTE approaches for different highway scenarios in order to evaluate the impact of high mobility and vehicles' density. Performance evaluation show that LTE4V2X has better performances than DCP: more the vehicles number increases, more framework is efficient, in terms of overhead as well as LTE bandwidth usage or packet loss (packet loss remains at 2%, independently of vehicles' density or vehicles' velocity). Moreover, the velocity does not impact the LTE4V2X efficiency, whereas DCP efficiency decreases when the vehicles velocity increases.

Our future work directions are to extend LTE4V2X to real-time applications and dissemination applications.

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