Auto-Adaptive Multi-Hop Clustering for Hybrid Cellular-Vehicular Networks

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***Abstract*—In this paper, we consider a hybrid vehicular network, in which vehicles transmit data via the cellular network and dispose of a Vehicle-to-Vehicle (V2V) interface. In this context, we propose an auto-adaptive multi-hop clustering algorithm, which optimizes the usage of the cellular radio resource under the constraint of a maximum packet loss rate (PLR) in the V2V network. The larger the V2V-based clusters are, the higher the data compression ratio at the cluster head is, and the smaller the amount of required resource on the cellular link becomes. However, PLR becomes higher due to the collisions on the V2V channel when increasing the number of hops for cluster enlargement. The proposed algorithm thus dynamically adapts the maximum number of hops in clusters according to the vehicular traffic density. Through simulations, we show that it performs better in terms of aggregated cellular data and packet loss rate than any fixed-hop clustering algorithm in a dynamic scenario.**

I. INTRODUCTION

Connected vehicles play a major role in the IoT universe. Multiple initiatives and ideas have blossomed to provide the driver with a rich source of traffic and environmental information in real time, as well as an internet-based personal entertainment system. At the same time, vehicles themselves become, in turn, a mine of valuable data that can significantly improve performance and broaden the horizon of possibilities in larger systems, from traffic management to energy consumption.

In order to make vehicular networks a reality, several Radio Access Technologies (RATs) have been (and some are still) under study. For instance, in Europe, the ETSI ITS G5 standard proposes IEEE 802.11p for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connectivity, in the 5.9 GHz band. Fourth generation (4G) cellular networks have also been proved to meet performance requirements for vehicular network applications. LiFi for V2X communication is also promising but it is, to this day, in very early stages of development.

There is one important difference when it comes to using the cellular network: as the used spectrum is licensed and managed by operators, the quality of service is expected to be better than in unlicensed technologies like IEEE 802.11p but the cost of using it is also higher. There are several possible economic models for the payment of the cellular access cost, but all of them have an impact for the final consumer. Data volume quotas may also be imposed. Cellular network access becomes, thus, a precious and scarce resource.

On the other hand, V2V protocols such as IEEE 802.11p, however free of any monetary cost, do not necessarily (and easily) provide internet access. For this, Road Side Units (RSUs) can be deployed but are often regarded as too costly, while cellular infrastructure is already available. Furthermore, research shows that IEEE 802.11p can easily be congested, rapidly suffering from a high packet loss rate due to collisions.

In order to take advantage of the best of every technology, we propose to build clusters of vehicles, in which intra-cluster communications are ensured by IEEE 802.11p and can access the cellular network via the cluster head. To be more specific, a cluster is composed by a group of Cluster Members (CM) and a Cluster Head (CH), which generally takes a special role. In a multi-hop cluster, CMs are able to reach the CH potentially using other CMs acting as relay nodes along several hops.

In our model, we consider a scenario where vehicles have to periodically send data to the cellular network on the uplink, e.g., Floating Car Data for traffic management purposes. A reduction of the uplink cellular traffic can be achieved by aggregating and compressing this information at the CH, which is the only node using the cellular connection. CH can also locally broadcast information received on the cellular downlink, through the V2V network (such as local data requested to a Geographic Information System). However, a tradeoff arises when changing cluster size in terms of number of hops. The larger clusters are, the higher the data compression ratio at the CH is and the smaller the amount of required resource on the cellular link is. However, PLR becomes higher due to the collision on the V2V channel when increasing the number of hops.

In this paper, we propose an auto-adaptive multi-hop clustering algorithm for hybrid vehicular networks that will locally and dynamically change the maximum number of hops (thus increasing or decreasing cluster sizes) in order to maximize compression of the volume of data exchanged with the cellular infrastructure, while keeping the V2V packet loss rate below the maximum tolerable threshold.

The article is organized as follows: In Section II we provide a brief review of the related work. We introduce our model and algorithms in Section III. Subsequently, the simulation results are presented and analyzed in Section IV. Conclusions are drawn in Section V.

II. RELATED WORK

Clustering algorithms became long time ago a fundamental tool in the operation of wireless ad-hoc networks, and more recently a new branch of these algorithms emerged for the particular context of vehicular networks [1]. Most of these algorithms were primarily focused on improving classic clustering metrics, such as cluster lifetime, or cluster head changes. A subsequent survey [2], in response to the growing amount of alternatives, classified vehicular clustering algorithms in function of the different techniques and purposes of vehicular cluster formation (predictive, multi-hop, MAC-based, etc.).

We focus on *multi-hop* clustering algorithms [3], [4], [5], because it is the only way a cluster can expand its borders beyond the V2V communication range, thus allowing for better information aggregation and compression capacity. There is, however, a trade-off: given the nature of the radio interface, rebroadcasting messages can quickly lead to a *broadcast storm*, leading to the saturation of the radio channels in use.

In recent years, some clustering algorithms have been specifically designed or adapted for working in hybrid vehicular networks [6], [7], [8]. However, in these proposals, the cellular network is only used as a gateway to the Internet and never participates on the cluster formation. The drawback of these approaches is that the decision criteria for electing cluster heads often leads to an excessive amount of them, which in the case of multi-hop clustering produces an undesirable effect: if the number of hops is increased, the PLR will consequently increase, degrading the V2V network performance, but there will be little or no gain in terms of cluster size and data compression, since every vehicle will try to join the nearest cluster head, at the smallest number of hops.

Rémy et al. in [9] propose to delegate the whole cluster formation to the cellular base stations. This however generates a lot of traffic in the cellular network, thus considerably increasing costs. The impact of the cluster size on the packet loss rate is not studied either. In this paper, we extend our previous work [10], which has shown the correlation between cluster size, data compression and packet loss rate. We now propose a clustering algorithm that dynamically changes the maximum number of hops, supervised by the cellular network. We also show via simulations in a dynamic scenario that our algorithm outperforms fixed-hop static algorithms.

To the best of our knowledge, none of the existing approaches of clustering in hybrid vehicular networks addresses the problem of achieving optimal cluster sizes for maximizing cellular data compression, while reducing the cellular network signalling overhead and keeping the V2V packet loss rate under control.

III. MODEL AND ALGORITHMS

A. Network Model

We consider a highway section where vehicles move in one direction[1]. We assume a scenario that corresponds to the multi-RAT environments that we expect to see in the upcoming 5G wireless systems: every vehicle is equipped with one transceiver for direct vehicle-to-vehicle communication, and another transceiver for cellular network access.

In this work, we study the data aggregation in the cellular uplink. Every vehicle has to send its identification and position to a distant Traffic Management Server at a rate of λ packets/s. If the vehicle does not belong to a cluster (i.e., it belongs to a cluster of size 1), it is obliged to send this information through its own cellular connection. If the vehicle is in a cluster c of size $N_c > 1$, it will send this information to the CH, which will aggregate the data collected from all the vehicles in the cluster and send it to the remote server. This way, the cellular network is constantly aware of the traffic density in every area, and is able to identify and locate every single vehicle that is not part of a cluster.

Any cluster c generates, for the cellular network, a traffic equal to $\eta(N_c)N_c\lambda$, where $\eta(N_c) \leq 1$ is a compression function performed by the CH. $\eta(N_c)$ may be a decreasing function of N_c. For simplification purposes but without losing generality, we assume $\eta(1) = 1$.

The total cellular traffic of the set of all clusters ($\mathcal{C}$) is, then:

$$\Lambda(\mathcal{C}) = \sum_{c \in \mathcal{C}} \eta(N_c)N_c\lambda, \tag{1}$$

where N_c is the number of vehicles in cluster c and $N = \sum_c N_c$ is the total number of vehicles.

We can now define the global compression ratio, α, as:

$$\alpha(\mathcal{C}) \triangleq 1 - \frac{\Lambda(\mathcal{C})}{N\lambda} = 1 - \frac{\sum_{c \in \mathcal{C}} \eta(N_c)N_c}{N} \tag{2}$$

Our objective is to maximize $\alpha(\mathcal{C})$ while respecting the constraint of keeping the Packet Loss Rate (PLR) below the acceptability threshold:

$$\max_{\mathcal{C}} \alpha(\mathcal{C}) \tag{3}$$

$$\text{s.t.} \;\; PLR(\mathcal{C}, \lambda) \leq PLR_{max}, \tag{4}$$

where PLR_{max} is an application specific constraint.

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[1] For the case of vehicles moving in opposite direction, there are multiple possible solutions. For the cluster formation process, the easiest way is to enhance the speed information in the Cooperative Awareness Messages by adding the angle (vectorial speed). If this information is not available, it can be deduced from two consecutive messages including position. The messages coming from a vehicle moving in an opposite direction can then be filtered from the cluster formation algorithm. The CH election algorithm would run separately for each direction.

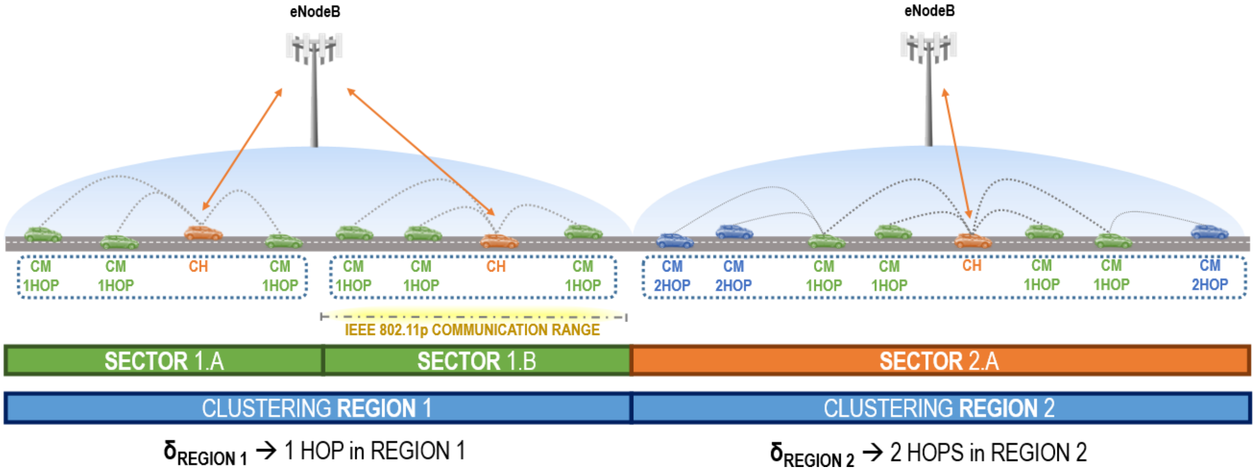


Fig. 1: **Model basics:** A clustering region can be served by one or more cellular base stations (eNodeB). In each region, the maximum number of hops is dynamically determined by the Auto-Adaptive Algorithm in function of vehicular density. A clustering region is divided into multiple clustering sectors. The length of the clustering sector is equal to the IEEE 802.11p communication range, multiplied by the maximum number of hops in the region. The algorithm ensures that in every clustering sector, there will be a Cluster Head. Only the CH exchanges data with the eNodeB.

B. *Auto-Adaptive Algorithm*

Our algorithm is made of two parts: a CH election algorithm (Algorithm 1) and a Hop adaptation algorithm (Algorithm 2).

For the purpose of these algorithms, the space is divided in **clustering regions** (see Figure 1), which correspond to the coverage of a single base station (or eNode-B). Every clustering region is characterized by a maximum number of hops H for the clusters that are formed there. Together with the V2V communication range, this maximum number of hops determines the **clustering diameter** (D) in this region. Every clustering region of length L_r is divided into **clustering sectors** of length D.

The CH election algorithm (Algorithm 1) is implemented in every base station for a single clustering region. Its role is to elect one CH in every clustering sector. It takes as an input the maximum number of hops H for its region provided by the hop adaptation algorithm. At regular intervals of $T_{election}$ seconds, Algorithm 1 verifies if there is a CH in every sector. If there is a sector where no CH is present, it elects the vehicle that is the closest to the sector center as CH.

The hop adaptation algorithm (Algorithm 2) is also implemented in every base station for a single clustering region and is responsible for dynamically adapting the maximum number of hops H as a function of the vehicle density. For every number of hops H, there are two thresholds $\Delta_{H-hop_{min}}$ and $\Delta_{H-hop_{max}}$. If the observed density is less than $\Delta_{H-hop_{min}}$, we allow clusters to be larger and set $H := H+1$. If the density is higher than $\Delta_{H-hop_{max}}$, packet loss rate may increase, so we decrease the number of hop by one. Note that we may have $\Delta_{H-hop_{min}} \neq \Delta_{(H+1)-hop_{max}}$ to account for hysteresis. The hop adaptation is done every $T_{adaptation}$.

Algorithm 1 Cluster Head Election Algorithm (Base Station)

```
Initialisation:
Set maintenance period $T_{election}$.
Set the maximum number of hops $H$, an output of the
hop adaptation algorithm
Set IEEE 802.11p radio range $R$ and compute the clus-
tering diameter $D = 2 \times R \times H$.
Divide the clustering region into $S = L_r/D$ sectors.
Routine:
For $t = nT_{election}$, $n = 1, 2, ...,$ do
    For $s = 1, 2, ..., S$, do
        If there is no CH in $s$ then
        Elect as CH the vehicle that is the closest
        to the center of $s$.
        Endif
    Endfor
Endfor
```

As the vehicle density may be heterogeneous inside a clustering region, taking decisions based only on average density may lead to poor performance. To tackle this issue, we define a **Predictive Analysis Zone** (PAZ) at the beginning of the clustering region (typically one fourth of the region length in simulations). The vehicle density is measured in both the PAZ (δ_{PAZ}) and in the rest of the region ($\delta_{\overline{PAZ}}$). We then take the decision about the number of hops based on $\max\{\delta_{PAZ}, \delta_{\overline{PAZ}}\}$. The idea is to benefit from the specific movement pattern observed on a highway section in order to avoid peaks in packet loss rates: if the density is higher in the PAZ, we anticipate the hop change; if the density is higher in the rest of the region, we account for the worst case. The computational complexity of our algorithms in function of the number of vehicles present in each sector

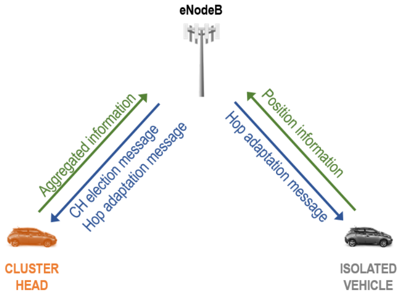


Fig. 2: **Message exchange over the cellular network:** In the simple simulated model, only Cluster Heads and eventually isolated vehicles (technically, CHs of a cluster of size one) are the only ones that access the cellular network, exchanging the information seen in this figure.

can be characterized as $O(n)$. Knowing that the input size is constrained to the elements of a clustering sector, there can be no scalability problems.

Algorithm 2 Hop adaptation algorithm (Base Station)

```
Initialisation:
Set maintenance period $T_{adaptation}$.
Set maximum number of hops $H := H_{default}$.
Set the Predictive Analysis Zone as the first $L_{PAZ}$ = min($\frac{L_r}{4}$ , $4 \times R$) meters of the clustering region.
Set triggering thresholds $\Delta_{k-hop_{min}}$ and $\Delta_{k-hop_{max}}$ for $k = 1, 2, 3$.
Routine:
For $t = nT_{adaptation}$, $n = 1, 2, ...$, do
    Compute vehicular density $\delta = \max\{\delta_{PAZ}, \delta_{\overline{PAZ}}\}$.
    If $\delta < \Delta_{H-hop_{min}}$ then
        $H := H + 1$
        Notify all vehicles in the clustering region and Algorithm 1 of the change in $H$.
    Endif
    If $\delta > \Delta_{H-hop_{max}}$ then
        $H := H - 1$
        Notify all vehicles in the clustering region and Algorithm 1 of the change in $H$.
    Endif
Endfor
```

Figure 2 shows the message exchange between the base station (eNode-B) and the CHs or isolated vehicles. Table I shows the different variable definitions used in the description of the algorithms.

IV. SIMULATIONS

A. Simulator Configuration

The algorithms presented in Section III have been coded and evaluated, using the Veins [11] framework, that synchronizes a traffic simulation running in SUMO (Simulation of Urban MObility) [12] and a full-stack network simulation in OMNeT++.

TABLE I: Model variables and their simulation values.

Name	**Description**	**Value**
H	Number of hops	*(dynamic)*
$H_{default}$	Default number of hops	3
L_r	Length of the clustering region	5 km
R	IEEE 802.11p communication range	800 m
D	Clustering diameter (length of a clustering sector)	2.R.H
$T_{election}$	Timer for CH election control	10 s
$T_{adaptation}$	Timer for hop number adaptation control	40 s
L_{PAZ}	Length of the Predictive Analysis Zone	*(formula)*
δ_{PAZ}	Vehicle density in the region's PAZ	*(dynamic)*
$\Delta_{1-hop_{min}}$	Density threshold for adaptation from 1 hop to 2 hops	17.5 vehicles/km
$\Delta_{2-hop_{min}}$	Density threshold for adaptation from 2 hops to 3 hops	5.5 vehicles/km
$\Delta_{2-hop_{max}}$	Density threshold for adaptation from 2 hops to 1 hop	22.0 vehicles/km
$\Delta_{3-hop_{max}}$	Density threshold for adaptation from 3 hops to 2 hops	7.0 vehicles/km

The map consists of a 10 km long highway segment, divided into two *clustering regions* of equal length. In terms of vehicular traffic, the tested scenario consists of three consecutive flows of very different densities: from 0 s to 2500 s, 100 vehicles enter the highway section at an average inter-arrival time of 25 s. From 2500 s to 4500 s, a second flow of 200 vehicles will enter the highway section at an average inter-arrival time of 10 s. And finally, starting from 4500s, a flow of 1600 vehicles will enter at an average inter-arrival time of 1 second. The vehicular density in the two clustering regions (and in the entire highway segment) in function of time can be seen in Figure 3.

Numerical values for algorithm parameters are shown in Table I. Density thresholds have been taken from our previous work [10]. We assume a compression function equal to $\eta(N_c) = 1/N_c$, where N_c is the cluster size. A performance evaluation in terms of $\alpha(\mathcal{C})$ and PLR is made, comparing the Auto-Adaptive Algorithm to the fixed-hop static algorithms that use only the CH Election Algorithm without hop adaptation and assuming 1, 2 or 3 hops respectively.

We define the Packet Loss Rate in the V2V network as the ratio between lost packets (due to incorrect decoding or collisions) and correctly received and decoded packets. Since we have a medium that uses radio broadcast, defining which messages we should consider as lost may not be evident. In our case, the network simulator evaluates the path-loss of the radio signal, and can generate the associated random errors. We count a packet loss in the case where the received signal power is enough to trigger the decoding process, but it leads to a decoding failure. We also count a packet loss for the case of a collision in the radio channel. The maximum tolerable PLR depends on the specific constraints of each application. For a Cooperative Awareness (CA) service, we have set our threshold at 10%. In our model, the amount unicast V2V messages (mostly for joining and leaving clusters) is negligible compared to the amount of broadcast CA messages.

B. Simulation results: Response to strong vehicular density variations

The results are presented in separate figures for the different traffic flows for an improved reading and analysis, but the reader should keep in mind that they are part of a single, continuous simulation.

During the first part of the simulation, a very light traffic density is introduced. Vehicles are too far away from each other and, as we can see in Figure 5.a, the 1-hop algorithm is unable to form big enough clusters, and is severely penalized in its aggregation performance when compared to the others. The best aggregation performance goes, then, for the maximum number of hops: the 3-hop algorithm leads at all times, and the Auto-Adaptive Algorithm follows its behaviour. In terms of PLR (see Figure 4.a), all the algorithms remain below 1%.

When the second flow of vehicles arrives at the mark of 2500 s, curves gradually change, and the 3-hop algorithm goes beyond the PLR acceptability threshold of 10%. The Auto-Adaptive Algorithm then changes the number of hops, from 3 to 2, and we can see a significant reduction of the PLR after the peak we get when the new flow starts (see Figure 4.b). The Auto-Adaptive Algorithm's compression curve starts following the 2-hop curve.

Finally, for the highest density (Figures 4.c and 5.c), the PLR curves of 2- and 3-hop skyrocketed, leaving 1-hop as the only viable possibility. The Auto-Adaptive Algorithm triggers a hop change again, resolving another PLR peak, while its aggregation performance follows the curve of 1-hop.

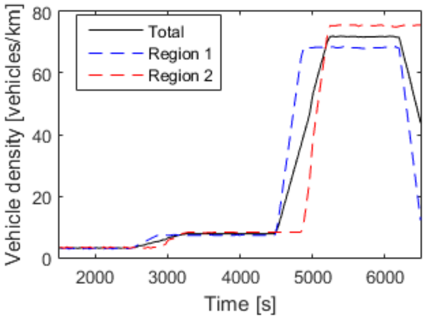
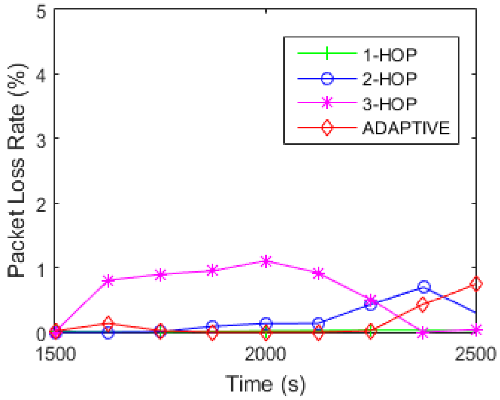
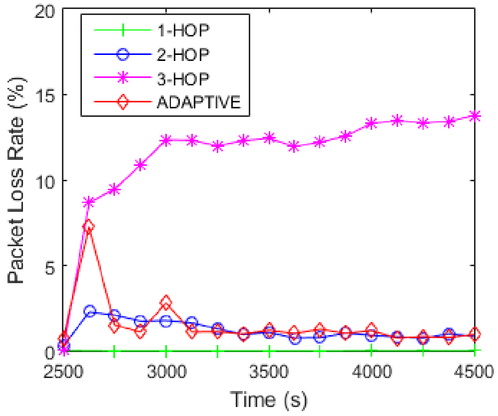


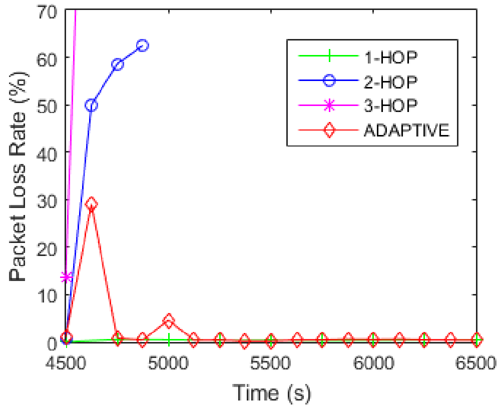
Fig. 3: Vehicular density in the tested scenario in function of time, measured in regions 1 and 2, and the density in the entire highway segment comprising both regions.



(a) Low density



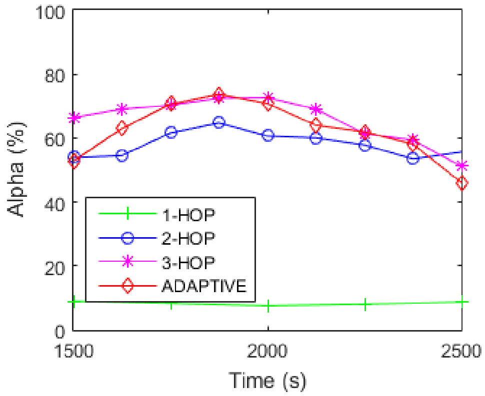
(b) Medium density



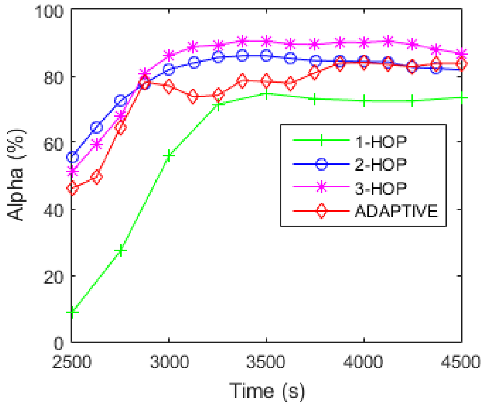
(c) High density

Fig. 4: Packet Loss Rate (PLR) in function of time for the tested scenario. Comparison between 1-,2- and 3-hop configurations vs. Auto-Adaptive Algorithm.

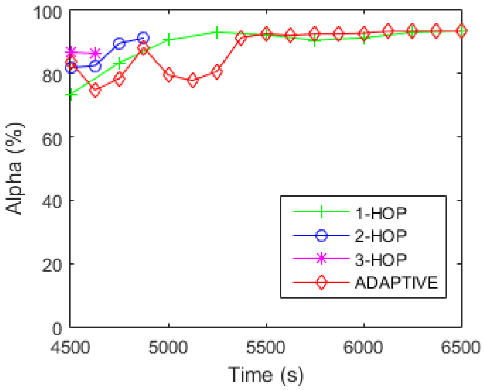
We now show that the signalling induced by the Auto-Adaptive Algorithm is negligible compared to the number of messages saved by clustering. We first compute the number of messages with destination the cellular network generated by every vehicle and the number of messages sent by the CHs. During the simulation of 6500 s, we observe a gain of $516,184$ messages thanks to compression. During the same simulation, we have also observed 8 hop number change notifications, and 98 cluster head proclamations (for a total of 1900 vehicles in the simulation). In the worst case, we thus have 98×8 change notifications and 98 CH elections for a total of 882 signalling messages used by our algorithm. This represents only 0.17% of the savings in terms of number of messages. Even if messages have different lengths, this rough estimation shows that the signalling associated to our



(a) Low density



(b) Medium density



(c) High density

Fig. 5: Cellular data consumption reduction (Alpha) in function of time for the tested scenario. Comparison between 1-,2- and 3-hop configurations vs. Auto-Adaptive Algorithm.

algorithm is negligible.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have considered a hybrid vehicular network, where vehicles are clustered using IEEE 802.11p and communicate via their cluster head to a cellular network. We have presented an Auto-Adaptive multi-hop clustering algorithm that dynamically changes cluster sizes (by adapting the maximum number of hops in function of the traffic density) with the objective of reducing the usage of the cellular network resource while maintaining the packet loss rate in the V2V network below a certain threshold. The algorithm performs the cluster head election and hop adaptation in the base stations of the cellular network. Using an ITS simulation fraework, we show that the Auto-Adaptive Algorithm correctly adapts to extreme density changes, making the best possible reduction in cellular network usage (thus making important monetary savings at large scale), while respecting the imposed constraints of packet loss rate on the V2V network, guaranteeing that specific applications' requirements can be met. This method, despite being efficient from the point of view of network performance, raises the problem of the distribution of the communication costs in which CHs incur. An eventual deployment of this clustering method would need, beforehand, a definition of a set of fair distribution rules of these costs. This will be the object of future works inspired in models coming from the field of game theory.

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