Dynamic Cluster Size Optimization in Hybrid Cellular-Vehicular Networks

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Abstract—**Ground-breaking innovations in transport, such as autonomous vehicles, the European Local Dynamic Map (LDM) and related on-line services heavily depend on reliable vehicular connectivity. In the most likely scenario, hybrid vehicular networks will use the IEEE 802.11p protocol for vehicle-to-vehicle (V2V) communication, and the cellular network (e.g. LTE or 5G) as a gateway to remote servers. Both technologies have their own flaws as IEEE 802.11p available bandwidth drops quickly with the accretion of vehicles in the vicinity, and intensive cellular usage can be costly. In this context we intend to minimize this cost while ensuring system reliability.**

Clustering vehicles can significantly reduce cellular network usage when the Cluster Head (CH) is the only node that communicates with the cellular Base Station (BS) and also performs data aggregation. Other nodes communicate with the CH using multi-hop forwarding over IEEE 802.11p. There is however a tradeoff in cluster design. On the positive side, large clusters lead to high aggregation levels and thus low usage of the uplink cellular resources. On the negative side, large clusters also increase packet losses in the IEEE 802.11p network affecting communication reliability. In this paper, we study the impact of the number of communication hops on the average size of formed clusters, on data compression, and on IEEE 802.11p packet losses in various vehicle densities. We present a new clustering algorithm which delegates the CH election to the cellular BS, significantly improving the cluster formation compared to CH self-election algorithms. We propose a dynamic clustering approach that adapts the cluster size to the vehicle density and optimize data compression under the constraint of an acceptable IEEE 802.11p packet loss.

I. INTRODUCTION

Vehicular connectivity is the cornerstone of future Intelligent Transportation Systems (ITS), providing a substantial leap forward in road security, and paving the way for innovative services, from driving assistance to information and entertainment. However, the network protocol designed for connecting vehicles, IEEE 802.11p easily reaches congestion points [1], while the volume of data to be transmitted is important, even for basic services. The European standard ETSI ITS-G5, built over this protocol, establishes that every vehicle has to broadcast a Cooperative Awareness Message (CAM) at intervals as short as 100 ms, and Decentralized Environmental Notification Messages (DENM), which are sent upon a particular incident and usually require re-broadcasting. To this day, the initiative of some major players in the automotive industry is to equip their cars with cellular network interfaces, while keeping the use of this resource as low as possible for high costs reasons.

The most likely scenario seems to be that vehicles will have two network interfaces: cellular network (e.g. LTE or 5G) and IEEE 802.11p [2][3]. Messages for certain services, such as security, will be managed locally, while others will require access to remote servers. As the usage of the cellular network resources has a significant cost [4], it is essential that the information be aggregated before being uploaded whenever this is possible.

The most widely adopted approach for data collection and aggregation in vehicular networks (as well as in other environments such as wireless sensor networks) is clustering. This technique consists in creating groups of communicating devices in a geographical vicinity, where a member of the group is designated as a Cluster Head (CH) whose functions may vary depending on the application. In our case, this entity is responsible for gathering and compressing data received through the vehicle-to-vehicle (V2V) radio interface, namely IEEE 802.11p, and upload the aggregated information through the cellular network. In *multi-hop* clustering algorithms, the cluster size can be increased, extending the CH's coverage area by allowing packet forwarding between cluster members.

However, a trade-off must be made when designing a clustering algorithm with respect to its average size. On one hand, large clusters significantly reduce the cellular network access (thus, costs are minimized), yet packet loss in the V2V interface increases dramatically. On the other hand, small clusters ensure low packet losses in the IEEE 802.11p network, yet offer little or no compression, and hence raise the costs associated to the usage of the cellular network.

Our main contributions in this paper are:

- We show the impact of the maximum number of hops between a specific vehicle and its CH on the average cluster size, the data aggregation performance and the packet loss in the IEEE 802.11p network. At low vehicle densities, the number of hops should be maximized in order to increase data compression. At high vehicle densities, we observe that increasing the number of hops leads to unacceptable packet losses. Because of such unreliable communications, cluster sizes also decrease and affect data compression.

- We propose a new clustering algorithm, which delegates the CH election to the cellular BS. Compared to the VMaSC algorithm [5], which is based on a CH self-election, our algorithm results in larger clusters for the same maximum number of hops. As a consequence, data compression is more efficient with our solution. There is no need of constant, but at least occasional cellular network coverage.
- Based on extensive simulations, we identify the best clustering parameters (e.g. maximum number of hops) adapted to specific conditions (e.g. dense or light traffic). Finally, based on these results, we propose a conceptual architecture and dynamic algorithm for choosing the maximum number of hops in order to maintain packet loss always under an acceptable threshold, and data compression as high as possible.

This article is organized as follows: we give an overview of the related work in Section II; we describe our model and formulate our problem in Section III; clustering algorithms are presented in Section IV and evaluated in Section V; our dynamic approach is proposed in Section VI; and Section VII concludes the paper.

II. Related work

A. Clustering algorithms

Clustering techniques are applied in multiple kinds of networks, and there are already multiple algorithms specifically designed for vehicular ad-hoc networks (VANETs) [6]. These algorithms usually take into account the specificities of vehicular movement (heading, relative speed, etc.) in order to improve the cluster's stability. Bali et al. [7] categorized VANET clustering algorithms according to either the way the clusters are formed (predictive, active, passive) or the formed structure and the communication characteristics (Back-bone based, MAC based, etc.).

Our interest is focused on *multi-hop clustering algorithms* [5], [8], [9]: by using message forwarding, the clusters can be larger than the communication range of the Cluster Head. Increasing the number of hops makes more intensive use of the radio resources, but can potentially increase the data aggregation ratio towards the cellular network. Besides, it improves connectivity in areas with light traffic, where vehicles are at a certain distance from one another. However, when there are too many vehicles, if the message forwarding is not controlled, the radio interface will be easily saturated.

It is worth mentioning that there is a specific type of MAC-based clustering algorithms that make use of *Time Division Multiple Access (TDMA)* [10], [11] techniques. These algorithms assign a time slot to each Cluster Member (CM) in order to avoid collisions and hence ensure the arrival of messages. In the absence of other control mechanisms, it is a decent choice for scenarios with very dense traffic and a heavy use of the radio resources. Nevertheless, we have decided to focus on multi-hop algorithms because:

- Even if theoretically multi-hop and TDMA approaches are not incompatible, applying time division to a distributed network over radio interface seriously hinders its scalability, and would be especially inefficient when combined with multi-hop forwarding.
- Current ITS standards clearly determine the use of the CSMA/CA channel access control, which would be incompatible with real MAC-level TDMA. Implementing a pseudo-TDMA on superior layers would certainly be less efficient.
- Alternative approaches can be considered in order to reduce packet loss on the V2V link, but multi-hop clustering is strictly necessary for optimal data aggregation and the consequent cellular traffic reduction.

Another type of MAC-based clustering algorithms proposes an interesting approach that consists in performing *Space Division Multiple Access (SDMA)* [12][13]. The road is divided in fixed segments, and each of these segments is assigned a specific transmission time. It is a very straightforward way for organizing transmission times and reducing collisions but, the segments being of fixed size, performance drops considerably with high density. In our proposal we will use the notion of (dynamic) space division, not for channel access, but for leader election.

The vast majority of the literature in this area has been conceived under the assumption that only V2V communication is available. Initial hypothesis supposed the deployment of numerous IEEE 802.11p Road Side Units, an assumption that is being left behind because of its deployment costs. As we have discussed before, the limitations of IEEE 802.11p and the high desirability of a connection to distant servers in order to deploy innovative services have obliged car manufacturers to include cellular connectivity in their new developments. Little research for improvements in clustering techniques has been done ever since taking into account this assumption. These works are being discussed in the following paragraphs.

B. Heterogeneous clustered VANETs

In heterogeneous vehicular networks, we have at least two different communication technologies, usually a protocol for V2V communication and a cellular network. Most of the research in this area focuses on gateway selection algorithms (a gateway in this case would be a node that acts as a nexus between two networks). In [2], Benslimane et al. propose a clustering-based gateway management method between IEEE 802.11p and UMTS (3G). They focus on the selection of the best gateway candidates according to the UMTS Received Signal Strength (RSS). A similar work is carried by Zhioua et al. in [3], where they use fuzzy logic to select the best gateway node between a clustered VANET and LTE, with the novelty of considering traffic class as a priority in order to incorporate QoS constraints in the gateway election.

Another research direction focuses on the cluster formation problem. For example, [14] propose an interesting architecture intended to guarantee the arrival of CAM messages in the specific scenario of intersections. They create a *cluster region* around the intersection (the cluster regions are fixed). Every CAM message is transmitted via LTE. Once a vehicle enters a clustering region, it starts broadcasting beacons (specific to the clustering algorithm, not CAM) through the WiFi interface (the authors have chosen IEEE 802.11b instead of IEEE 802.11p because of its popularity and cost, but specify that they are interchangeable) in order to form a cluster. Once a cluster is formed, it is assigned a specific WiFi channel, and CHs are the only entities authorized to send CAM messages through LTE so that vehicles in different roads will be aware of the presence of vehicles near the intersection ahead. This considerably reduces the amount of CAM messages transmitted under the mentioned hypotheses, and proves to be a correct solution for the intersection problem. Yet, even though the architecture has a clever design, the application scenario is very limited due to the fixed nature of the *cluster regions* in a rather small area. There are other proposals for cluster formation designed for different goals or specific scenarios as the one presented above, see e.g. [15], [16].

Rémy et al. present in [17] an architecture called LTE4V2X, an approach which centralizes the clustering formation process, delegating it to an eNodeB (the base station of an LTE cellular network), in order to speed it up and save overhead traffic in the IEEE 802.11p spectrum. Furthermore, they implement an internal TDMA in each cluster in order to send the cooperative awareness information (position, velocity and heading). This last measure ensures collision avoidance. However, in the results shown by the authors, we see that even though the overhead traffic in IEEE 802.11p is considerably decreased, the LTE overhead raises dramatically, even compared to the overhead generated in IEEE 802.11p by DCP, a decentralized clustering protocol which does not make use of the cellular network. So we see that LTE is treated as an abundant resource, and the economic factor is not considered as a priority.

To the best of our knowledge, no specific research has been done concerning the analysis of the problem of balancing cluster size in order to find equilibrium between IEEE 802.11p packet loss and cellular access costs. In this paper, we try to make a clear analysis of this conflict that we consider to be critical since it compromises, on one hand, the correct functioning of the system, and on the other hand, its economic feasibility.

III. Model and problem formulation

We consider a vehicular network consisting of vehicles that circulate on a highway section of fixed length L_s and made of L lanes. On every lane vehicles arrive at periodic instants, every T seconds, at the beginning of the section. Vehicles circulate at constant speed until the end of the section where they leave the network. We assume that the whole highway section is covered by a single cellular BS towards which vehicles have to send information at a rate of λ packets/s.

Assuming a clustering algorithm is implemented, this traffic can be either directly transmitted to the BS or conveyed by a CH. When a vehicle belongs to a cluster of size 1 (i.e., it is isolated), it transmits its information to the BS using uplink cellular radio resources. When included in a cluster c of size $N_c > 1$, this traffic is sent to the CH using IEEE 802.11p protocol and the CH aggregates the information coming from CMs and sends the result to the BS.

The traffic generated by the cluster c for the destination BS is then $\eta(N_c)N_c\lambda$, where $\eta(N_c) \leq 1$ is a compression function performed by the CH that may be a decreasing function of N_c. Without loss of generality, we can assume that $\eta(1) = 1$. We define a *cluster partition* as a set of non-overlapping clusters that includes all the vehicles of the network. In the following, we will consider only cluster partitions with clusters having a maximum of H hops between any CM and its CH.

As a consequence, the total traffic generated by the vehicular network on the uplink of the cellular network for a given cluster partition $\mathcal{C}$ can be written as:

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

where $\mathcal{C}$ is the set of all clusters, and N_c is the number of vehicles in cluster c. We denote $N = \sum_c N_c$ the total number of vehicles in the network. We now define the global compression ratio of the clustering partition $\mathcal{C}$ as:

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

Note that α is also the average compression ratio. For this cluster partition and the considered traffic model, we can compute a Packet Loss Rate $PLR(\mathcal{C}, \lambda)$, which is a function of the cluster partition and the amount of traffic.

Our problem is for a given traffic condition λ to maximize the average compression ratio under the constraint of an acceptable packet loss rate:

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

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

where PLR_{max} is an application specific constraint.

IV. Algorithms and architecture

Two different multi-hop clustering algorithms are evaluated and compared: an algorithm where CHs are self-elected by using a minimum relative speed metric, and another one where the CH election is delegated to the cellular BS.

A. Cluster Head Self-Election

In this first approach we have chosen to implement an existing algorithm called VMaSC [5]. We have slightly modified the original algorithm in order to use the Cooperative Awareness Messages (CAM) of the European ETSI ITS-G5 standard as a replacement for the algorithm's regularly exchanged beacons. Some of the needed information is indeed already transmitted periodically on CAMs (ID, position, speed). We have also extended the definition of CAM messages in order to include the necessary information needed for the cluster formation process: (i) the individual calculation of the minimum relative speed in the observable *k-hop* vicinity; (ii) the parent node ID (i.e., the CM acting as a hop to the CH, when not directly connected to the CH); (iii) and the CH ID.

With this minimum incorporation to the CAM format, we are able to significantly reduce the algorithm's overhead. The only messages specific to the clustering process are occasional CH_ADVERTISEMENT, JOIN_REQUEST and JOIN_RESPONSE messages.

In this algorithm, making use of the information collected during a fixed initial period, if a vehicle detects that it has the lowest relative speed with respect to the set of vehicles it can see in its vicinity, it elects itself as CH and starts broadcasting CH_ADVERTISEMENT messages. Any vehicle wanting to join the cluster has to send a JOIN_REQUEST message, and the incorporation is only effective once it received a JOIN_RESPONSE from either the CH (if directly connected) or its parent node.

B. BS-based Cluster Head Election

A major drawback of the CH self-election algorithm is that it generates too many CHs. To overcome this issue, we propose to delegate CH election to the local cellular BS, see Algorithm 1. The main idea is to divide the highway section into segments, whose length depends on the IEEE 802.11p radio communication range and the maximum number of hops and elect as CH in every segment the vehicle that is the closest to the center point of the segment. This process is updated every T seconds. This algorithm can be extended to a more complex map by dividing it into road sections in the same direction and covered by a single BS and applying the procedure described in Algorithm 1.

Algorithm 1 BS-based CH Election Algorithm

Initialisation:
Set maintenance period T.
Set IEEE 802.11p radio range R, maximum number of hops H and compute the clustering diameter $D = 2R \times H$.
Divide the highway section into $S = L_s/D$ segments.
For $t = nT$, $n = 1, 2, ...$, **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

This algorithm does not require constant cellular coverage, since in case of losing coverage elected CHs will remain in that state, and the cluster would not break, and vehicles would be able to join, leave or change clusters. However, it is difficult to predict how the quality of formed clusters would degrade with time after being disconnected from the cellular network. One possibility would be to let a cluster switch to CH self-election if cellular coverage is lost for a long time.

Cluster handover process is yet to be modelled, but even under current assumptions, since CHs coming from other clusters would be detected as such, only optional CH re-centring procedures would be needed in order to maintain the CH centrality criterion that gets it elected in first place.

V. Simulation and results

The simulations have been run using the Veins [18] framework, which synchronizes the traffic simulator SUMO (Simulation of Urban MObility) [19], and the network simulator OMNeT++.

A. Simulation parameters

The base network traffic consists of the mandatory CAMs setting the frequency at the minimum value of 1 Hz (every vehicle emits, then, one CAM per second). These messages are the basic element of the Local Dynamic Map (LDM).

We assume an aggregation ratio $\eta(N_c) = 1/N_c$, where N_c is the cluster size. The length of the highway section is $L_s =$ 5 km, and the number of lanes is $L = 3$. We will consider that, for the system to work in a secure and reliable manner, the packet loss rate on the V2V radio interface, PLR_{max}, cannot be higher than 10% [1]. A total of $N = 60$ vehicles is simulated in each round. The average vehicle speed is 16.6 m/s. The vehicle inter-arrival distance varies between 1 s and 20 s. This is equivalent to say that we will analyze the variations of our metrics in function of the vehicle density, since increasing vehicle inter-arrival time implies reducing vehicle density and vice-versa. The reader should keep in mind this inversely proportional relationship.

The maximum number of hops is set to $H = 1$, 2 and 3 in separate simulation runs (See Figure 1), for each of both clustering algorithms (CH self-election and BS-based CH election). We set T as the average duration for a vehicle to traverse the estimated cluster diameter D.

The communication with the cellular Base Station is simplified for the simulations shown here: it is modelled as always available (perfect coverage) and without failures.

B. Results and analysis

1) Maximum number of hops vs. packet loss rate: In Figure 2, we show the packet loss rate as a function of the inter-arrival time for different maximum number of hops and for the CH self-election algorithm. Observed trends are similar for the BS-based CH election algorithm. We can clearly see that the amount of lost packets grows drastically for high vehicular densities, and the situation gets much worse for every supplementary hop we allow. The reason lies in the broadcast storm effect arising in highly dense

[1] We estimate that, for a continuous Cooperative Awareness service beaconing, a maximum of 10% packet loss can be tolerated. For any application involving real-time streaming, these thresholds are usually around 2%. In any case, it is desirable that urgent security messages can be delivered through a dedicated channel, since for critical real-time applications, a packet loss ratio as low as 1% is still undesirable.

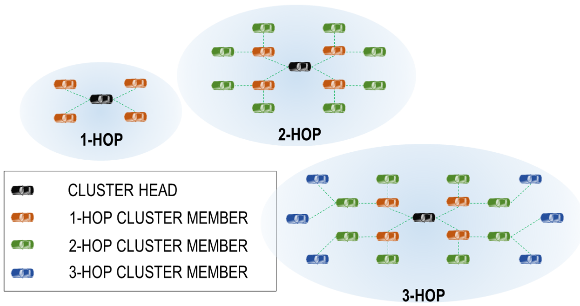

Fig. 1. Illustration of the three examples of multi-hop clusters studied in our simulations, with the maximum number of hops varying from 1 to 3.

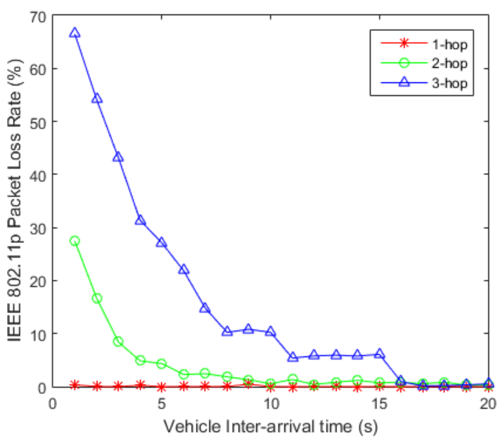

Fig. 2. IEEE 802.11p packet loss rate as a function of the vehicular inter-arrival time, for different numbers of hops and the CH self-election algorithm.

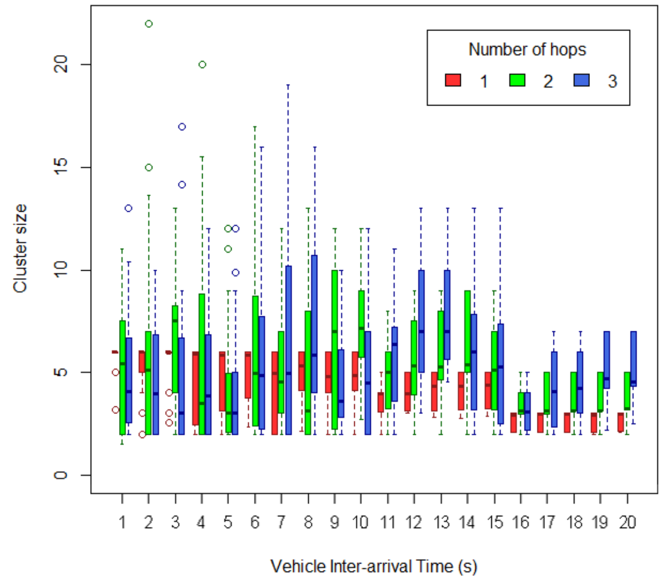

Fig. 3. Box plot showing the sizes of the clusters formed by the CH self-election algorithm as a function of the vehicle inter-arrival time, for different maximum numbers of hops.

multi-hop networks when some packets are broadcast. This effect is amplified when these packets are rebroadcast over an increasing number of hops.

In this figure, we can see that there are some vehicular densities for which 2 or 3-hop clustering is incompatible with the requirements: below 10 arrivals per second (resp. 3 arrivals per second), the CH self-election algorithm with maximum 3 hops (resp. 2 hops) does not meet the packet loss rate constraint of 10%.

The simulation estimates the packet loss ratio for broadcast messages by counting the correctly and incorrectly decoded messages in the simulated network cards situated in the transmitter's radio range.

2) Maximum number of hops vs. cluster size: Figures 3 and 4 show box plots of the cluster sizes obtained, for different vehicular densities and number of hops, with the CH self-election algorithm and the BS-based CH election algorithms respectively.

As expected, we can see that at intermediate to high inter-arrival times (i.e., at low to intermediate vehicle densities), as the the number hops increases the average cluster size increases as well. When the number of hops is high (especially in the case of 3-hop clusters) however, increasing the vehicle density has a contradictory effect. High vehicle density indeed leads to high packet losses and CHs cannot properly communicate with the potential CMs. This implies a decrease of the average cluster sizes. When the number of hops is small however, increasing the vehicle density also increases the average cluster size.

Our BS-based CH election algorithm proves to perform much better in terms of cluster size, showing an unambiguous direct effect between increasing the number of hops, and increasing the cluster size. In the case of the CH self-election algorithm, since too many CHs are proclaimed, increasing the number of hops leads to little or no gain in terms of cluster size (and thus, presumably, in cellular traffic savings).

3) Global compression ratio: The evolution of α as a function of the vehicle inter-arrival time is expressed, in terms of percentage, in Figure 5 for both algorithms and for $H = 1$, 2 and 3 hops. From intermediate to high inter-arrival times (i.e., low to intermediate densities). Conclusions are clear: allowing more hops is the best strategy and our BS-based CH election algorithm outperforms the CH self-election algorithm. This is due to the fact that the packet loss rate is maintained at an acceptable value, so that more hops allows for larger cluster sizes, which in turn improve the data compression ratio. As our algorithm creates less CHs, the data compression ratio is also improved. At low inter-arrival times however, the packet loss rate becomes unacceptable, so that large clusters fail to form. Performance with $H = 3$ thus become the worst for both algorithms. We however note that this phenomenon arises at a lower inter-arrival time with our algorithm, which illustrates the superiority of the BS-based CH election algorithm.

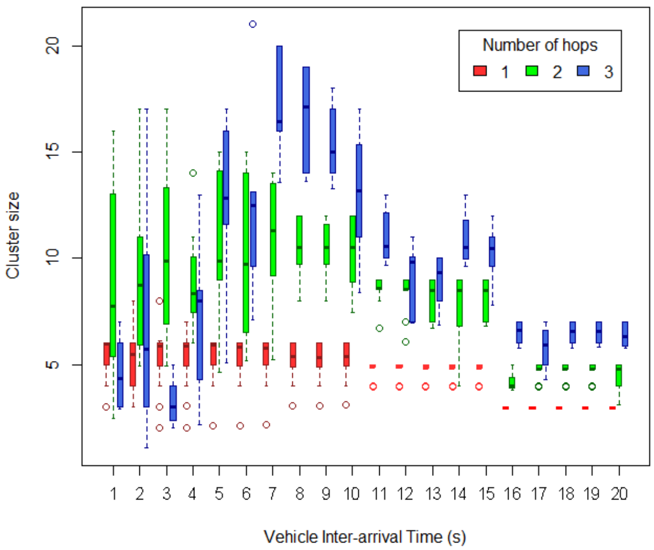

Fig. 4. Box plot showing the sizes of the clusters formed by the BS-based CH election algorithm as a function of the vehicle inter-arrival time, for different maximum numbers of hops.

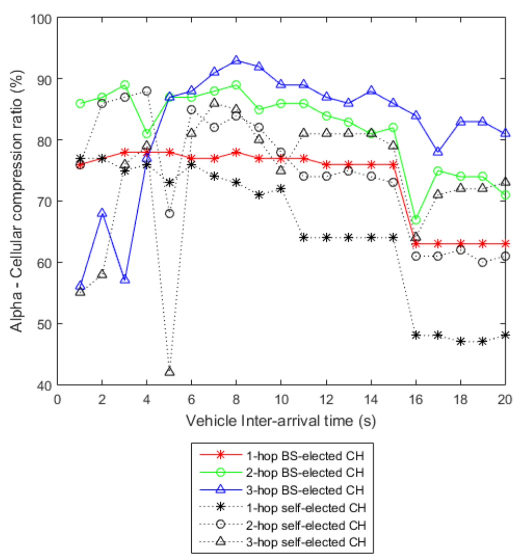

Fig. 5. Global data compression ratio: Comparison between CH self-election and BS-based CH election algorithms, for different maximum numbers of hops.

VI. A PROPOSAL FOR DYNAMIC ADAPTIVE CLUSTERING

In light of the previous results, we propose to dynamically adapt the maximum number of hops as a function of the observed vehicle density, so that the cellular network usage is minimized under the constraint of a maximum packet loss rate. There are two possible ways for determining the right moment to trigger the maximum hop number change:

- Bottom-up: Since messages have a serial identifier, a CH can detect when a certain packet has not been received. Evaluating the number of lost packets from all of its children, the CH can make an estimation of the packet loss rate and decide on its own when to increase or decrease the maximum number of hops. Once notified by the CH, the BS can add or remove CHs if necessary.
- Top-down: The BS has a global vision of the vehicles in the covered area. It can, thus, easily deduce the vehicle density and eventually estimate or retrieve information about the IEEE 802.11p packet loss rate. When these values stabilize below or above the tolerated threshold, the BS can trigger the hop number change and, at the same time, make the necessary alterations to the local set of elected CHs.

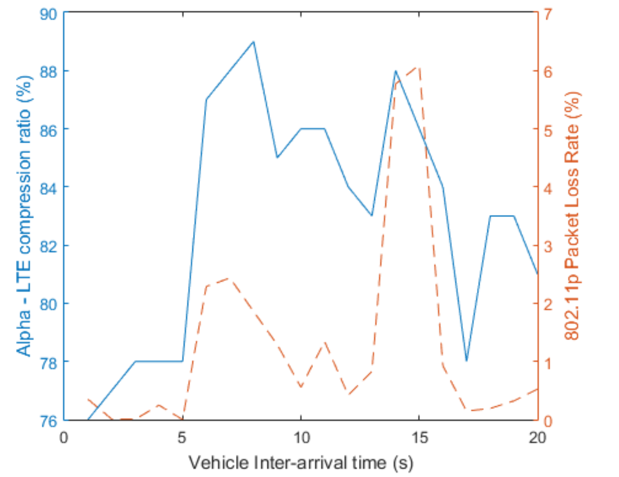

Fig. 6. Global data compression ratio (solid line) and IEEE 802.11p packet loss rate (dashed line) for a dynamic adaptation of the clustering algorithm (by changing the number of hops) as a function of the vehicle inter-arrival time.

Figure 6 shows the expected outcome of this dynamic adaptation in terms of packet loss rate and global data compression ratio α assuming a top-down implementation. We can see that packet loss is always below $PLR_{max} = 10\%$ and α is always at very high levels. This estimation is obtained considering that, either facing an increasing or decreasing vehicle density, the system will wait until tendencies in packet loss ratio get consolidated under or over a buffer zone slightly below the maximum tolerable threshold, fixed in our examples at 10%. This way, we determined for which vehicle density values we use the results obtained for 1, 2 or 3-hop simulations as an estimator of the packet loss ratio and the cellular compression.

VII. CONCLUSIONS AND FUTURE WORK

We have shown and quantified the impact of the maximum number of hops and vehicular density on the size of the formed clusters, and consequently on cellular information aggregation efficiency. We also proposed a new algorithm which, by delegating the Cluster Head election to the cellular Base Station, lets us profit much more efficiently of the advantages that increasing the number of hops can provide in terms of average cluster size.

It comes to evidence that in high vehicular densities, 1-hop clustering is the most convenient option, since it has negligible packet loss (while 2-hop and 3-hop clustering largely surpass the maximum tolerated levels). As vehicular density decreases, the most convenient option in terms of data compression is to switch first to 2-hop clustering then to 3-hop clustering as the IEEE 802.11p packet loss rate decreases. This is why we proposed a dynamic adaptive clustering technique and two possible implementations (namely top-down and bottom-up).

Finally, some orientations for our future work are:

- Analyzing the possible utility of having different maximum hop number for different clusters.
- Implementing the use of different radio access channels for different clusters and study the effect on packet loss rate.
- Test the effectiveness of the dynamic adaptive clustering algorithm on a testbed.
- Reducing packet loss rate by implementing tree structures for smarter message forwarding inside a cluster.

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