Vehicular Network Self-Organizing Architectures

Mohamed oussama Cherif[1,2], Sidi Mohammed Senouci[1], and Bertrand Ducourthial[2]

[1]Orange Labs, Core Network Laboratories, 2 Avenue Pierre Marzin, 22307, Lannion, France
[2]Laboratory Heudiasyc UMR CNRS 6599, Université de Technologie de Compiègne, 60200 Compiègne, France

***Abstract* — Nowadays, Vehicle Communication (VC) represents an interesting item for research and industry communities since it brings an efficient way to improve the transport quality. Nevertheless, VC faces a number of new challenges, in particular due to the extremely dynamic network topology and the large variable number of mobile nodes. To overcome these problems an effective solution is to define a self-healing and robust self-organizing architecture that facilitates the network management task and permits to deploy a wide panoply of services. Depending on the application deployed on the top of the vehicular network, it may require either a proactive or a reactive self-organization architecture. In this paper, we introduce CSP and CGP, which are respectively proactive and reactive cluster-based self-organizing protocols. The two solutions are cross layer and they structure intelligently the vehicular network in permanent manner by portioning roads into adjacent segments seen as geographic fix clusters. When the proactive solution, CSP, can be used for security issues or to provide a large panoply of services, the reactive solution, CGP, is mainly used to perform data collection and aggregation. In our work, we analyze the performances of both CSP and CGP using a simulation environment and realistic mobility models. We compare them to existing solutions and show that they permit performance improvement.**

***Index Terms* — Vehicular networks, Self-organization, Clustering, Routing, Broadcast, Info traffic applications**

I. Introduction

Vehicular Ad hoc Networks (VANETs) can be identified as Mobile Ad hoc Networks (MANETs) where mobile nodes are wireless technology equipped vehicles [1], [2]. The aim of vehicular networks is to provide communications among neighboring vehicles and between vehicles and nearby fixed equipments. Such networks have some own characteristics that have important implications for designing solutions. We can cite (i) high mobility: VANETs are associated with a very dynamic environment (ii) partitioned network: the dynamic traffic nature may lead to isolated clusters of nodes (iii) geographically constrained topology: in VANETs, nodes move along roads with fixed topology, and (iv) large scale: VANETs may extend over large areas.

To overcome some of these challenges, a self-organizing architecture has to be set up to simplify the network management task and to permit the deployment of a lot of services. This architecture should take advantage of node properties to issue a global virtual structure enabling the network self-organization. It should be sufficiently autonomous and dynamic to deal with any local change. The self-organization favors the collaboration between the different local properties, not interesting in themselves, to establish useful global information or services and to permit an optimized packets routing between nodes.

One way to support efficient communication between nodes is to develop a wireless backbone architecture; this means that some nodes have to be selected to form the backbone. Over time, the backbone must change to match with the changes in the network topology as nodes move around. The algorithm that selects the members of the backbone should evidently be fast, but also should require as little communication between nodes as possible to avoid an important overhead. One way to solve this problem is to group the nodes into clusters, where one node in each cluster functions as cluster head.

As shown in Table 1, there are two ways to self-organize the vehicular network by using a proactive organizing architecture or a reactive one.

TABLE I
SELF-ORGANIZING ARCHITECTURES

Self-Organizing Architectures	
Proactive Architecture	Reactive Architecture
Created at the beginning and then maintained continuously	Created On-Demand
Covers the whole network	Covers a road portion
Support all kinds of services	Permits traffic gathering in critical zones

In this paper, we introduce CGP (Clustered Gathering Protocol): a reactive self-organizing protocol. The goal of CGP is to gather data when needed (occasionally) from all vehicles in order to offer different info traffic services [5]. But first, we present CSP (Cluster-based Self-organizing Protocol); a vehicular network proactive self-organizing architecture that is based on geographical clustering to ensure a permanent self-organization of the whole network. In fact, CSP adapts itself to vehicular network characteristics and permits to improve inter-vehicles or vehicle-to-infrastructure connectivity without producing a great overhead. Then it permits not only to deploy dissemination and gathering services but also other services like file sharing and Internet access, etc.

The two solutions are complementary since CSP is more adapted to urban environment. So CGP can be deployed to perform traffic gathering in highways.

This paper is structured as follows. Section II exhibits the most relevant related works. Then, in Section III and IV, we introduce respectively the proactive self-organizing protocol, CSP, and the reactive one, CGP. Finally, we conclude the paper and give some perspectives to our work in Section V.

II. Background

In this section, we give an overview of the existing self-organizing structures and we evoke some related works.

A. Self-organizing structures

Most researches suggest virtual backbone [6] and clustering [7] as most efficient structures to self-organize the MANET and to achieve scalability and effectiveness in broadcasting.

The idea of defining a virtual backbone structure is brought from the wired networks. The principle of this solution is to constitute a dorsal of best interconnected nodes. The only constraint is the judicious choice of backbone members (BM) to avoid the rapid loss of interconnection between BMs. The most pertinent technique to construct the virtual backbone is the MCDS (Minimum Connected Dominating Set) structure [3], [4]. The MCDS is a subset of nodes defined to form a stable and persistent backbone with minimal cardinality. Each other node must be connected to at least one BM.

The second self-organizing structure is clustering. It is the partition of the network in homogeneous zones named clusters. Each cluster has at least one cluster head and a set of members. Generally, the members of one cluster have some common characteristics as contiguous velocities or coordinates, etc. Cluster-based solutions represent a viable approach in propagating messages among vehicles. In this approach, only nodes members of the cluster are enabled to relay broadcast messages. Thus, the clustering structure is usually used as a support of backbone structure since both of them are devoted to arrange the information dissemination in a VANET.

In the next subsection, we will discuss some related works which use these structures to self-organize the network.

B. Related works

Many works [10], [11], [12] within the context of VANET introduce the concept of virtual backbone and clustering scheme in the aim of self-organizing the network.

In [10], authors define two main methodologies to organize the vehicular network in peer spaces: Cluster-based organization and Peer-Centered organization. The cluster-based organization considers the associative nature of the traffic for forming groups of peers with similar characteristics. These clusters can be dynamic or fixed. In peer-centered organization, each peer defines, constructs and maintains its own virtual peer space (VPS). Different VPSs can overlap.

In [11] the authors take inspiration from the organization of the cellular network in adjacent cells to propose the division of the service area into a number of sub service areas (SSA).

One base station (BS) is settled in each SSA. The SSA area is set larger than a service coverage area of one BS. Then, a self-organizing process is executed in each SSA to ensure the communication between the BS and Mobile Stations (MS) that are outside its coverage area. In this method, some MSs may be selected as relaying MS, so they support two radio communication channels, one for link establishment control and the other for data transmission. The link establishment process in this proposition is classified into three types. First, an MS tries to establish a direct link with the BS of its SSA. If this is not possible, it tries to establish a link with its BS using relaying MSs. The third alternative is to establish a link with a neighboring BS using relaying MSs. Finally, if the MS is isolated from the other MSs of its SSA and the neighboring SSAs it increases progressively its transmission power until it succeeds to communicate with another MS. So, it uses it to relay its packets to the BS associated with the new neighbor.

In [12] the authors propose, within the context of VANET, DBA-MAC (Dynamic Backbone Assisted MAC), a proactive distributed scheme to form a virtual backbone in a dynamic way in order to send a broadcast alert message to a group of potential receivers in a risk zone. To create the backbone, a node elects itself as a backbone member (BM) then it broadcasts a beacon message to spread the backbone creation process impulsion. After that, all the receivers enter in a distributed MAC access phase based on contention mechanism to elect the next backbone member. Once elected, each BM sends a beacon message to continue the backbone creation process. Backbone members have the highest priority in accessing the channel and then they can relay the broadcast messages. This is supported by the MAC scheme called Fast Multi-Hop Forwarding (FMF). Since a reactive scheme for repairing the backbone would need break-detection capability and overhead, DBA-MAC proactively refreshes the backbone.

On one side, in the solution proposed in [11], MSs do not need to collect topology information of the whole network, but they only have to collect topology information of their SSAs. This shortens the time for construction and maintenance of the network, considerably. In this proposition, an eventual node connectivity loss affects only some nodes in its SSA (the nodes that uses it as relay to reach the BS). In [12], if BM_n loses the connectivity with BM_{n+1}, the entire network will be affected. On the other side, the solution introduced in [11] is not really adapted with road topology and a node is not sure to find a relaying gateway without increasing its range. This problem does not exist in DBA-MAC since all the backbone members reach each others, so a node can be associated all the time with at least a backbone member.

In the solutions we propose, we adapt the proposition introduced in [11] to vehicular networks by portioning roads in segments seen as fixed clusters and self-organizing vehicles in each segment. Then, a cluster head is elected for each segment, without generating a great overhead, to act as backbone member. This self-healing architecture is robust and permits the deployment of many services without important overhead. In the following two sections we will describe our proactive and reactive self-organizing protocols: CSP and CGP.

III. Cluster-based Self-organizing Protocol (CSP)

CSP is conceived to proactively self-organize the vehicular network in order to smooth up the nodes mobility effects without generating a great overhead. In this section, we give a brief description of CSP function, and present its added value compared to other vehicular network self-organizing solutions.

A. CSP architecture

CSP functions span MAC and network layers, it forms temporarily single hop clusters to get rid of the hidden node problem.

Accordingly, an access point is able to communicate with vehicles which are outside its physical transmission range. The area where vehicles can be reached by the access point via multi-hop communication is called ECA (Extended Communication Area). An ECA is divided into L-length segments as shown in Figure 2. Vehicles located in the same segment form one cluster. The associate idea is to assign a state to each vehicle. Three states are possible: i) HEAD: the vehicle in charge of routing the segment packets. ii) SUPER_MEMBER: a vehicle that had been a HEAD of its segment, and its current role is to route packets to one of the neighboring segments. iii) MEMBER: vehicles that are neither HEAD nor SUPER_MEMBER.

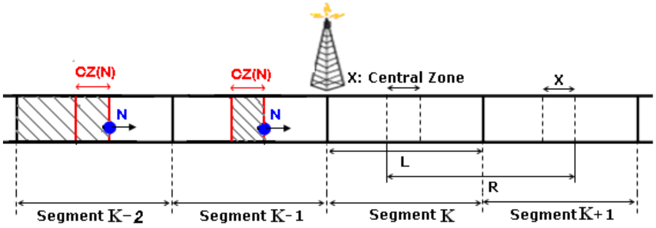

Fig. 2. ECA of an access point.

Each L-length cluster/segment is composed of one head, one super member and several members. It is split in one central zone and two lateral zones (see Figure 2). The respective lengths of central and lateral zones are X and (L-X)/2. The choice of X value is very important since it inversely affects cluster size and cluster lifetime. Another parameter to take into account is the communication range R. In fact, each vehicle in the central zone of one segment must be able to communicate with every other vehicle in the central zone of the adjacent segments.

In the rest of this section we consider the download link because we focus on I2V communications for the performance evaluation but we must notice that CSP permits also to deploy services on upload link. If N is a vehicle, the abbreviations we will use are summarized in Table 2:

TABLE II

ABBREVIATIONS

ABBREVIATION	DESCRIPTION
X_N and V_N	position and algebraic velocity
S(N)	current segment
CZ(N)	neighboring segments of S(N) respectively closer and farther away from the access point
$CZ_+(N)$ and $CZ_-(N)$	respectively the farthest and closest border of CZ(N). They verify: $[CZ_+(N) - CZ_-(N)] . V_N \geqslant 0$
H(N), M(N) and SM(N)	head, member and super member of S(N)
TABLE(N)	table in which the head stocks requisite information about its members

B. CSP protocol

CSP consists of two modules: (i) dynamic selection of heads, and (ii) management of vehicles transition between segments.

1) Head selection

Initially, a head is elected for each segment in a distributed way. Each node N in the CZ of its segment computes an *IE_Factor* (Initial Electing Factor) that reflects the expected time to be spent in CZ(N). Then, it waits for a backoff duration which is inversely proportional to its *IE_Factor* before broadcasting a *Head_Decl* in S(N). When they receive the *Head_Decl*, other nodes of the segment stop sending their *Head_Decl*, set their own states to MEMBER, register the information of N as new head, and send a *Member_Req* to it. Therefore, N registers each of them in TABLE(N). Meanwhile, the elected head checks periodically its position and estimates its next one according to (1).

$$Next\_Pos(N) = X_N + V_N . P_{H\_Check} \qquad (1)$$

If N considers leaving CZ(N) after Δ_t ($\Delta_t < P_{H\_Check}$), it broadcasts a *Head_Resign* in S(N). Each member M of S(N) who receives the *Head_Resign* and fulfills the conditions (2) or (3) is a candidate to be H(N).

$$(V_M . V_N > 0) \quad AND \quad (M \text{ does not yet reached } CZ_+(N)) \quad (2)$$

$$(V_M . V_N < 0) \quad AND \quad (M \text{ is situated in } CZ(N)) \quad (3)$$

Then, it computes an E_Factor (Electing Factor) which reflects the estimated time before reaching $CZ_+(N)$.

The formulas (2) and (3) correspond respectively to vehicles in the hashed zones in segments K-2 and K-1 in Figure 2.

Each candidate waits for a backoff duration which is inversely proportional to its E_Factor then it sends a *Head_Req* to N. When N receives the *Head_Req* sent by a candidate M it sends a *Head_Ack* to M in which it includes TABLE(N). When M receives the *Head_Ack* it saves the segment information in a new table (TABLE(M)), changes its state to HEAD and broadcast a *Head_Update_Ack* in S(M). Hence, N can remove its table and change its state to SUPER_MEMBER and other segment members change their head and stop sending *Head_Req* if they are candidates. After changing its state to SUPER_MEMBER, the previous Head (N) runs as gateway: it routes the packets sent by the new head to the neighboring segment. This argues the fact that the area of candidates circulating in the same way than the previous Head N (Figure 2) is wider than the one of candidates circulating in the opposite way.

2) Inter-clusters transition

When entering in a new segment, a node N verifies periodically its position and estimates the next one using the same formula as (2) with a period P_{Check}. If N considers leaving its segment after Δ_t ($\Delta_t < P_{Check}$), it broadcasts a *Mbr_Add_Req*. Receiving this request, the head of the next segment adds N to its table and sends an *Mbr_Add_Notif*. When N receives the *Mbr_Add_Notif*, it sends an *Mbr_Remove_Req* to its head. Receiving this request, the current head removes N from its table and sends an *Mbr_Remove_Notif*. When N receives the *Mbr_Remove_Notif*, it updates its segment and its head and sets its state to MEMBER.

C. F-CSP variant

F-CSP (Fundamental CSP) is a variant of CSP in which potential candidates to HEAD task are vehicles situated in the CZ of the segment. The other nodes are excluded even if they circulate in the same way that the current head. In this variant, only two states are defined, HEAD and MEMBER. As heads are in the CZ of their segments, and making allowance of (1), neighboring heads can reach each other without requiring any super member. The problem with this solution is the limited life cycle duration of clusters comparing with CSP.

D. CSP: Performance evaluation

In this sub-section, we evaluate the performances of an advertising diffusion application (downlink) in a self organized ECA, and we compare them with those of a classical broadcast where each node broadcasts the packet one time.

1) Simulation setting

In primer approach we have chosen to simulate one ECA using Qualnet simulator [9] and VanetMobiSim [8]. All the key parameters of the simulation are summarized in table 3:

TABLE III
SIMULATION PARAMETERS

SIMULATION PARAMETERS			
Simulator	Qualnet [9]	Simulation Time	30 s
Nbr of Segment	8	Comm. Range	500 m
Length of Segment	350 m	$P_{H\ Check}$	0.4 s
Central Zone	150 m	P_{Check}	0.5 s
Road width	30 m	Data Packet Size	512 bytes
Vehicle Velocity	30 – 50 km/h	Nbr of Vehicles	100 – 300
Mobility Model	Extended VanetMobiSim	Packet Sending Rate	0.1 s - 0.7 s

2) Simulation results

The performance evaluation we achieved focuses on two aspects of our solution. First, we studied the protocol main characteristic (life cycle duration of clusters). Then we considered CSP for an application performance evaluation, where we examined if it realizes the advertising broadcast properly, by analyzing the overhead, the packets delivery ratio and the end-to-end delivery delay. In this section we are going to present, only, the strongest aspects of CSP.

a) Overhead

In Figure 3, we evaluate the overhead of CSP, F-CSP and the classical broadcast as function of vehicle density. We can observe that the increase in network density induces an increase in the routing overhead for both CSP and F-CSP, which is totally expected since the number of control messages depends on the number of nodes. On one hand, the most overhead in case of CSP and F-CSP is due to the organizing architecture maintenance (e.g. head election, inter-segment transition) and only a cut-amount is due to the advertisement diffusion. Therefore if we increase the number of advertising packets, the overhead produced in case of CSP and F-CSP changes slightly. On the other hand, overhead generated in case of classical broadcast without auto-organizing architecture is due to the fact that all vehicles broadcast the advertising messages. So, if we increase the number of advertising packets, the overhead increases linearly (broadcast storm problem).

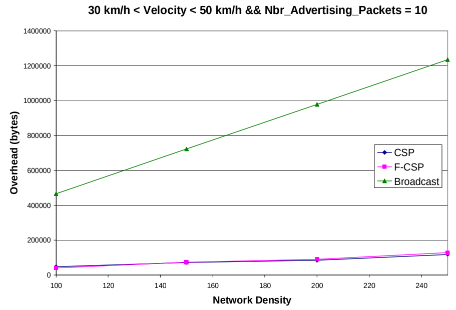

Fig. 3. Overhead vs. network density.

b) Delivery ratio

In Figure 4, we set the packets sending interval to 0.1s, and we vary the number of vehicles. We remark that the obtained delivery ratio is still upper than 90% apart from the density of the network. On the other hand, the values obtained with the classic broadcast fall to 60% which is mainly due to contentions since all vehicles have the right to broadcast data.

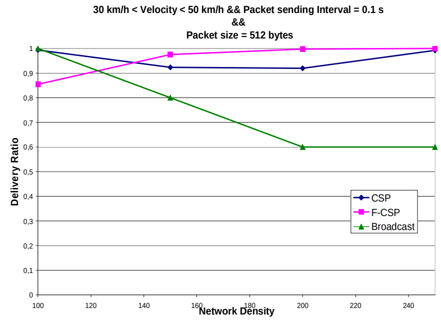

Fig. 4. Delivery ratio vs. network density.

IV. CLUSTERED GATHERING PROTOCOL (CGP)

After introducing CSP, our proactive self-organizing protocol, we describe in this section CGP the reactive self-organizing protocol. CGP is a protocol that uses the same segment organizing architecture and is particularly adequate for hybrid vehicular sensor networks. This new technology uses different kind of sensing devices available in new vehicles, to gather information about the driver's environment (speed, acceleration, temperature, seats occupations, etc.) in order to provide a safer, more efficient and more comfortable driving experience. CGP will allow data gathering and aggregation using the free-frequency communication medium (IEEE 802.11p, for example) before sending the valuable aggregated data to the operator via a cellular link. Thus CSP will reduce the traffic load on the operator network.

A. CGP architecture

CGP organizes the network only when needed and do not maintain the self-organized structure as in CSP. As in CSP the road is divided in virtual segments seen as fixed clusters. We assume in CGP that the transmission range of a base station (BS) covers all the associated segments.

B. CGP protocol

In this subsection we present the different steps of the execution of CGP. Each step starts periodically and has a predefined duration. Figure 5 explains the function of CGP.

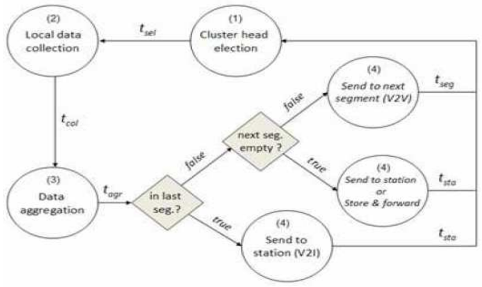

Fig. 5. CGP overview.

The step (1) in the algorithm is the cluster head election phase; it allows a set of nodes in a segment, to decide which one of them will gather the information in the next phase. In (2), the elected cluster head collects the data from all the nodes in its segment, then it aggregates them (phase 3). When a cluster head reaches the step (4) of CGP, if it is in the closest segment to the station, it sends the collected data; else, it either sends to the next cluster head toward the BS, or sends them directly to the station or makes a store & forward, depending on the initial configuration of CGP.

1) Head selection

The segment head election algorithm is similar to CSP. Each node considers itself as head till it gets a *Ch_Announce* message from another node or till the cluster head election period ends. The *Ch_Announce* message contains the identifier of the sender and its position. Nodes calculate a backoff time after which they are supposed to send their *Ch_Announce*. If a node *i* receives a *Ch_Announce* message from *j* and *j* has a better position, then *i* cancels its *Ch_Announce* message.

It should be noted that the backoff duration is a random bounded integer that depends on the node proximity to the segment end position. It is calculated using Formula 4.

$$t_{BO}(i) = Rand(0, t_{collect}) + Priority(Position(i,t), SegEnd) \quad (4)$$

Rand(x,y) is a function that returns a uniform distributed integer bounded between x and y, Priority(x, SegEnd) is a function that returns a period correlated with the distance between the node and the segment end position, thus, the closer is the node to the segment end, the shorter will be the period. Position(i, t) is the node's i position at an instant t and $t_{collect}$ is the gathering period duration.

2) Local data gathering

During this phase, all nodes in the segment send in unicast their sensed data to the cluster head using a mechanism similar to DCF (Distributed Coordination Function) presented in 802.11. Each node waits for a random bounded backoff time. At the end of this time, it sends a RTS to the head. Then, the head acknowledges the reception by sending a CTS (Clear To Send) message. Finally, the node sends its data to the head.

3) Data aggregation

Each head aggregates the collected data in its segment. In our particular case study, each node sends its identifier, position and orientation. Thus, the cluster head can calculate the number of nodes in its segment, and the average speed.

4) Inter-segment dissemination

When a cluster head is not in the closest segment to the base station, it automatically broadcasts its data to the next head in the direction of the BS. The head who receives these data, aggregates them with its own segment data.

5) Segment-BS communication

There are two situations where a cluster head can send its information to the BS: (i) if there is no cluster head in the following segment and (ii) if it is on the closest segment to the BS. In both cases, the node aggregates the data and sends them to the BS using a cellular communication.

6) Inter-segment dissemination

CGP can be configured to do store & forward instead of sending directly to the base station when the next segment is empty. In such situation, the node keeps the data in its memory during a parametric time, and waits for a cluster head in the next segment or till the node is in the closest segment to the BS.

C. CGP: Performance evaluation

1) Simulation setting

All the key parameters of our simulation are summarized in the following table:

TABLE IV
SIMULATION PARAMETERS

SIMULATION / SCENARIO		MAC / CGP	
Simulation time	600s	MAC protocol	802.11b
Map size	2500m x 2500m	Capacity	2 Mbps
Mobility model	VanetMobisim	Trans. Range	~266 m
Number of seg.	18	CH election duration	1 s
Nodes	50 - 1000	Data Gathering duration	3 s
Vehicle velocity	0 – 108 km/h	Aggregation duration	~0.1 s
Segment length	100 m	Dissemination duration	1 s
Road length	1.8 km	Number of lanes	2
Road width	15 m	Store & forward	Not used

2) Simulation scenarios

Three scenarios are considered in our work. In the first scenario, each node sends its collected data (speed, position, etc.) individually and periodically to the base station. The aggregation in this case, is done at the provider level. (See Figure 6.a). In the second scenario (Figure 6.b), the local data gathering and aggregation are done at the segment level, as described in CGP. The aggregated data (average speed, number of nodes, etc.) are sent to the BS directly from the cluster head of each segment. The Telco provider will only aggregate the data from each segment. In the third scenario (Figure 6.c), CGP will be integrally executed in this scenario, from the cluster head election to the data dissemination to the provider.

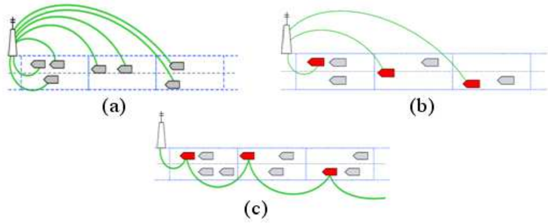

Fig. 6. Simulation scenarios.

3) Simulation results

We calculate the number of messages sent to the base station via the provider's cellular network. Thus, we can see in which scenario the data collection is the greediest in terms of cellular network usability.

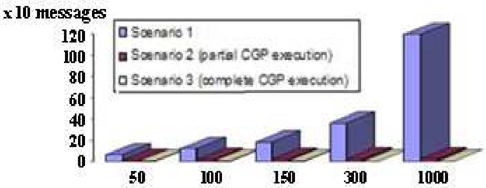

Fig. 7. Number of V2I messages.

As we can see from this chart, there is a clear difference between scenario 1, where all nodes use the provider's links, and the V2V scenarios where nodes use the vehicular sensors network to send their data to the provider. The number of messages is reduced by 91.2 % in scenario 2 and by 99.16 % in scenario 3.

TABLE V

OVERHEAD ON V2V AND V2I COMMUNICATIONS

NUM. NODES	NUMBER OF MESSAGES (V2V)		NUMBER OF MESSAGES (V2I)	
	SCENARIO 2	SCENARIO 3	SCENARIO 2	SCENARIO 3
50	7 213	7 630	836	320
300	46 745	48 670	2 016	160
1000	237 967	240 127	2 128	120

Table 5 shows a minor variation of the overhead in V2V communications between scenario 2 and 3. Thus, we can see that with a negligible overhead, a complete execution of CGP is preferred because it reduces more (over 8%) the provider's links utilization, particularly in urban environment where large number of nodes is handled.

TABLE VI

OVERHEAD VS SPEED

AVERAGE SPEED (km/h)	NUMBER OF MESSAGES
0 – 20	34 413
20 – 50	34 659
50 – 80	35 805
80 – 110	35 165

Table 6 shows the number of CGP messages when we vary the speed average value for 200 vehicles. We can see that the number of messages is quite stable. Thus, nodes velocity does not affect CGP performances. Hence, we can conclude from these results the significant contribution of CGP in terms of decreasing the number of messages upon a provider's network.

V. CONCLUSION AND FUTURE WORK

Self-organization of a vehicular network is a very important issue since it facilitates the management task. There are two ways to self-organize the vehicular network: proactive and reactive self-organization. We introduced in this paper CSP and CGP our proactive and reactive organizing protocols that rely on clustering to permit an efficient backbone construction. CSP and CGP are deployed in hybrid vehicular networks to facilitate the management task and to permit the deployment of wide panoply of services. They allow service providers to better exploit/extend the existing infrastructure by overcoming its limitations using a low-cost multi-hop technology. CSP facilitates the deployment of all ITS and broadband applications based on data dissemination or data gathering and CGP is mainly used for traffic gathering.

We demonstrate via simulations that CSP is efficient for advertisement diffusion applications in term of routing overhead and delivery ratio since it organizes the network using a robust structure. We demonstrate also the feasibility of CGP for the info traffic application based on data collection since it reduces the number of exchanged messages without any loss of accuracy in the collected data.

Whereas CSP pemits to offer a large panoply of services and is more dedicated to urban environment, CGP can be deployed in urban environment and highways and it permits traffic gathering. These two protocols are collaterals.

We are currently extending this work by performing other extensive simulations in order to study the extension of CSP to handle the handover between the different ECAs. Later, we endeavor proposing our own MAC layer and routing protocol adapted with the described self-organizing architecture.

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