Stable Clustering for Ad-Hoc Vehicle Networking

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***Abstract*—Vehicular ad-hoc networks (VANETs) that enable communication among vehicles and between vehicles and unmanned aerial vehicles (UAVs) and cellular base stations have recently attracted significant interest from the research community, due to the wide range of practical applications they can facilitate (e.g. road safety, traffic management, pollution monitoring and rescue missions). Despite this increased research activity, the high vehicle mobility in a VANET raises concerns regarding the robustness and adaptiveness of such networks to support system applications. Instead of allowing direct communications between every vehicle to UAVs or base stations, clustering methods will potentially be efficient to overcome bandwidth, power consumption and other resource issues. Using the clustering technique, neighbouring vehicles are grouped into clusters with a particular vehicle elected as the Custer Head (CH) in each cluster. Each vehicle communicates with UAVs or base stations through the CH of the associated cluster. Despite the potential advantages, a major challenge for clustering techniques is to maintain cluster stability in light of vehicle mobility and radio fluctuation. In this paper, we propose a Stable Clustering Algorithm for vehicular ad hoc networks (SCalE). Two novel features are incorporated into the algorithm: knowledge of the vehicles behaviour for efficient selection of CHs, and the employment of a backup CH to maintain the stability of cluster structures. By simulation methods, these are shown to increase stability and improve performance when compared to existing clustering algorithms.**

***Index Terms*—Vehicular Ad-Hoc Networks, Clustering, Cluster Stability, UAVs, Networking.**

I. Introduction

Vehicular ad-hoc networks (VANETs) are highly mobile wireless networks, which consist of vehicles that communicate with each other in a multi-hop manner. VANETs are self-organising and rapidly deployable networks that ultimately do not require a permanent infrastructure [1], [2].

Whilst they are individually able to support a multitude of applications in a wide range of contexts, cooperation between vehicles and UAVs or cellular base stations, as depicted in Figure 1, can be extremely beneficial. For instance, road safety can be drastically improved. In Europe, the The European Telecommunications Standards Institute (ETSI) has even designated a specific type of broadcast message known as Cooperative Awareness Messages (CAMs), containing information relevant to safety related applications (e.g. vehicle speed and position)[3].

Networking between vehicles and UAVs or cellular base stations can keep the network connected in the event of disruptions due to obstacles, poor weather conditions or natural disasters that destroyed existing communication infrastructure.

Unfortunately, concerns on the robustness and adaptiveness of such networks to support system applications arise in light of the the high mobility that characterises the nodes in a vehicular ad-hoc network. A main challenge is handling the rapid changes in the network topology and vehicular density, which significantly affects the performance of the network [4], [5]. Furthermore direct communication between every vehicle and UAV or base station, can generate serious resource issues related to bandwidth, processing, and power consumption.

Clustering techniques, which aim to partition the ground network vehicles into virtual groups known as clusters (Figure 1), can provide an effective solution for the aforementioned problems. A vehicle is selected to be a Cluster Head (CH) to manage the communication amongst its Cluster Members (CM) as well as interacting with other layers of a cooperative network (e.g. unmanned aerial vehicles, road side units or cellular base stations) as in Figure 1. Therefore, clustering algorithms are particularly effective in limiting the channel contention assuring fair channel access to vehicles within the cluster. Moreover, by limiting the number of vehicles that can connect to UAVs or cellular base stations, clustering techniques can provide spatial reuse of resources such as the bandwidth.

Despite the potential advantages, a major challenge for clustering techniques is to maintain cluster stability in light of vehicle mobility and radio fluctuation. In this paper we propose a Stable Clustering Algorithm for vehicular ad hoc networks (SCalE), in order to address the aforementioned issues and facilitate the networking between clustered VANETs and UAVs or cellular base stations. Novel contributions of this work include:

- Presenting a stable cluster head selection scheme that is achieved using the knowledge of the vehicle's behaviour.
- Presenting a stable cluster maintenance scheme using a backup cluster head (CH_{Bkp}).

The rest of the paper is organised as follows. Section II briefly reviews the current literature on the topic. Section III presents the CH selection procedure and the features involved in the process. Section IV describes the selection process of a stable CH_{Bkp} and how the SCalE algorithm operates to maintain cluster structures. Performance results are presented in Section V, with concluding remarks provided in SectionVI.

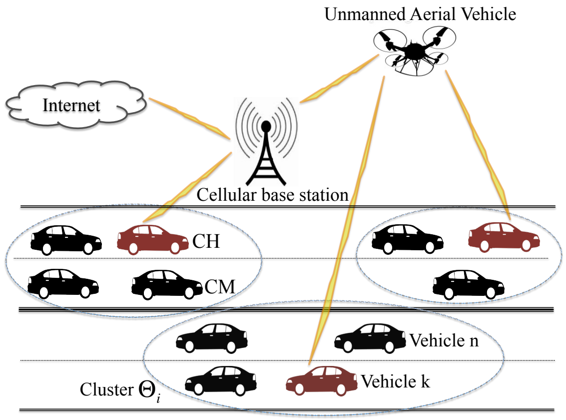

Fig. 1. Clustering scenario: vehicle cluster (circle dashed line) with cluster head (faded red), grouping all cluster members (black) within range. For networking with UAVs or cellular base station only CHs are allowed direct communication.

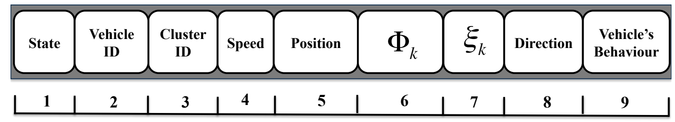

Fig. 2. Cooperative awareness messages (CAMs) structure of the information embedded. For simplicity every entrance is numbered.

II. Related Work

The first clustering algorithms were initially designed for Mobile Ad-Hoc Networks (MANETs) [6], [7], [8]. Among these MANET clustering algorithms the Highest-Degree [8] requires the vehicle with the highest nodal degree in the neighbourhood to undertake the role of cluster head.

Many clustering techniques designed for VANETs have also been proposed. A fast clustering algorithm that focused mostly on the rapid construction of the cluster rather than on the stable cluster head selection, is described in [9].

By contrast, mobility metrics are widely used to select a stable CH [10], [11]. The authors in [10] propose a clustering approach based on affinity propagation. The metrics used are a combination of current and future positions. Each node makes its clustering decision every clustering interval (CI). Depending on the length of the CI, which is arbitrary, the performance may rapidly diminish. The VMaSC algorithm, presented in [11], employs the average relative speed amongst neighbouring vehicles as a mobility metric, to select the CH.

The stability of the cluster head is improved in [12] due to lane detection. Every lane is assigned a different weight based on the traffic flow, which in turn will help evaluate the decision metric to elect the CH. However, lane detection is not always feasible, because it requires specific equipment.

III. Cluster Head Election

Algorithm 1 summarises the CH election process and cluster formation. Through periodical exchange of CAM messages every k vehicle can acquire information to calculate the CH selection index ξ_k. The vehicle with the lowest ξ will then be selected to be the CH, whilst all its free neighbours will become CMs.

A. CAM packet structure

The structure of the CAM used is depicted in Figure 2. It contains the following embedded information field of every vehicle k: vehicle state, vehicle ID γ_k, cluster ID (that is the cluster head ID), speed information v_k, position (x_k, y_k) (expressed as GPS coordinates), Φ_k defined as the set of all cars within range of vehicle k, CH selection index ξ_k, flow direction and vehicle behaviour B_k. For the sake of brevity, every data entry is henceforth denoted by a number as shown in Figure 2.

The vehicle state (field number 1 of the packet structure), can assume two different values: cluster head (CH) and cluster member (CM). Note that the vehicle's behaviour, field number 9 in Figure 2, represents a piece of information newly introduced in this work. This is a single bit of information $(0/1)$ which indicates whether the vehicle will leave the system (i.e. road way) at the next side exit. Obtaining such information is fairly straightforward since the vehicle itself can easily record this information either when it decides to take a turn or by combining input from the steering wheel and GPS tracking.

B. Cluster Head Selection Index

The CH selection index, ξ, is a parameter periodically calculated by every vehicle for the purposes of CH election. It is defined as a combination of different metrics, which are categorised as follows. The value of B_k is set to 1 if the vehicle intends to leave the system and to 0 otherwise, as expressed in (1). The information can improve the decision making process with regards to the election of a stable CH and backup CH (CH_{Bkp}). A vehicle willing to leave the system at the side exit cannot act as a stable CH, therefore the vehicle in question will be excluded from the election procedure. It represents the first step in the CH election, as it is used to filter out unstable candidates for the role.

$$B_k \doteq \begin{cases} 1, & \textit{if } k \textbf{ is } \textit{leaving the road way} \\ 0, & \textit{if } k \textbf{ is not } \textit{leaving the road way.} \end{cases} \tag{1}$$

The stability of the clusters can degrade rapidly in a highly mobile environment. Hence, the relative mean speed S_k, defined for every vehicle k, represents a good measure of the stability of a vehicle in a VANET. This metric is evaluated as the average difference in velocities v between the reference vehicle k and all N neighbouring vehicles within its range, i.e. those belonging to the set Φ_k. Moreover, the value is normalised to be within the range $[0, 1]$. The relative mobility is thus expressed as

$$S_k \doteq \frac{\sum_{n=1}^{N} |v_k - v_n|}{N \cdot max\{\Omega_k\}}, \tag{2}$$

where the normalising factor is the maximum value of the set Ω_k. This is defined as the set of all the vehicles speed differences $|v_k - v_n|$ within the set Φ_k, provided the vehicles are moving $(v > 0)$, and is formally expressed as

$$\Omega_k \doteq \{|v_k - v_n| \mid (v_k, v_n) > 0 ; \forall n \in \Phi_k\} . \tag{3}$$

Another metric that can be used to identify a stable CH is related to the vehicle position relative to its neighbours. A smaller normalised relative mean distance D_k indicates that the neighbouring vehicles are closer to the potential CH. Given the GPS coordinates of two vehicles k and n, we can write the x and y distance between the two at an arbitrary time as

$$\Delta x_{k,n} = |x_k - x_n|, \tag{4}$$

$$\Delta y_{k,n} = |y_k - y_n|. \tag{5}$$

Consequently, the mean relative distance D_k of vehicle k is defined as the mean Euclidean distance. Furthermore, normalising by the maximum value of the set Z_k, as shown in (6), makes S_k and D_k comparable:

$$D_k \doteq \frac{\sum_{n=1}^{N} \sqrt{[\Delta x_{k,n}]^2 + [\Delta y_{k,n}]^2}}{N \cdot max\,\{Z_k\}}. \tag{6}$$

The set Z_k is composed of all the Euclidean distances between the vehicles belonging to the set Φ_k, that is

$$Z_k \doteq \left\{ \sqrt{[\Delta x_{k,n}]^2 + [\Delta y_{k,n}]^2} \;\middle|\; \forall n \in \Phi_k \right\} . \tag{7}$$

Finally the CH selection index is evaluated as the sum of the normalised values of the mean relative speed and distances,

$$\xi_k \doteq S_k + D_k, \tag{8}$$

and as such will always fall in the range $[0, 2]$.

Upon periodical exchange of CAMs amongst all the vehicles in the system, the kth vehicle can record a list of all CH selection indexes ξ belonging to every nth vehicle in its neighbour's set Φ_k. The set of all ξ for every neighbour's set Φ_k is therefore defined as:

$$\Psi_k = \{\xi_n \mid \forall n \in \Phi_k\} . \tag{9}$$

Denoting γ_k as the ID of the vehicle k, the vehicle will be elected CH if its CH selection index ξ_k is found to be smaller than ξ_n, the selection index of any other vehicle n in range, that belongs to the set Φ_k:

$$CH = \{\gamma_k \mid \xi(\gamma_k) \le min\,\{\Psi_k\}\} \tag{10}$$

IV. Cluster Maintenance

A. Backup CH selection

After cluster formation, a maintenance phase comes into effect that aims to maintain cluster structure (Algorithm 2). To this end, another novel contribution of this work is introduced: the backup CH ($\mathrm{CH_{Bkp}}$). This is defined as the most suitable CM to become CH (without re-starting the CH election) if the current head is forced to resign from its role. The choice of a stable $\mathrm{CH_{Bkp}}$ is based on CH selection index ξ, and on the coverage that a vehicle has over its existing cluster. In choosing a stable $\mathrm{CH_{Bkp}}$, it is important that the vehicle selected will have the smallest repercussions in terms of losing CMs, and resulting reaffiliations. Consequently an additional metric, called cardinality (11), is introduced to take the vehicle coverage into account.

Algorithm 1 Cluster Head Election

Require: $\forall k$ in the system that do not belong to a cluster yet
for each kth vehicle **do**
    Evaluate ξ_k using (2), (6) and (8)
end for
for each kth vehicle **do**
    if k is in range of a CH_i **then**
        k$\leftarrow CM_i$
    else
        Start CH election process:
        Eliminate unstable vehicles with (1)
        if (10) **then**
            k$\leftarrow CH_i$
        end if
    end if
end for
go to CLUSTER MAINTENANCE

Let us define the ith cluster Θ_i as the set of all vehicles that belong to the same cluster and share the same CH. The CH keeps record of CMs in Θ_i, and also has knowledge of the neighbours set Φ_k of every kth CM, as shown in Figure 2. We can now define the cardinality degree index as

$$C_k \doteq |\Theta_i \cap \Phi_k| \quad \forall\, k \in \Theta_i\,, \tag{11}$$

where $\Theta_i \cap \Phi_k$ denotes the set of k neighbouring vehicles that are also part of the cluster Θ_i. Hence, C_k represents a measure of the coverage that vehicle k has over the cluster Θ_i, where a higher value means better coverage.

Let's call α_m the ID of the kth vehicle within a cluster Θ_i, with m representing an additional ordering index. The set Γ_{Ac} contains all the cardinality values $C(\alpha_m)$ of the CMs in Θ_i as shown in (12).

$$\Gamma_{Ac} = \{C(\alpha_1), C(\alpha_2), ..., C(\alpha_N)\} . \tag{12}$$

The CH sorts the CM IDs in descending order with respect to their cardinality; as the ordering index m increases the cardinality related to the vehicle with ID α_m decreases. The ordered set of CM IDs, A_C, is formally expressed as:

$$A_C \doteq \{\alpha_1, \alpha_2, ..., \alpha_N \mid C(\alpha_m) \ge C(\alpha_n), \forall\, m < n\} . \tag{13}$$

To select most suitable backup, the CH needs to acquire and store some additional information. Firstly, the CH needs a list Ξ_{As} of all CH selection indexes $\xi(\beta_m)$ belonging to every kth vehicle in its cluster Θ_i, where β_m denotes the personal ID of the kth CM within a cluster Θ_i. The set Ξ_{As} is therefore:

$$\Xi_{As} = \{\xi(\beta_1), \xi(\beta_2), ..., \xi(\beta_N)\} \tag{14}$$

The cluster member IDs are then sorted in ascending order with respect to their CH selection index ξ; as the ordering

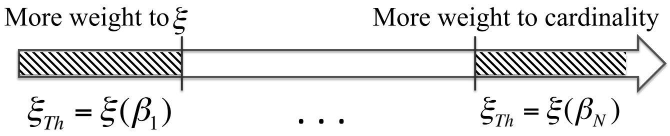

Fig. 3. How to choose ξ_{Th}

index m increases the ξ of the vehicle with ID β_m increases. The ordered set A_S of cluster member IDs is hence formalised as follows:

$$A_S \doteq \{\beta_1, \beta_2, ..., \beta_N \mid \xi(\beta_m) \leq \xi(\beta_n), \forall m < n\} \tag{15}$$

Finally, the new CH_{Bkp} will be the first CM in the cluster Θ_i with the highest cardinality degree (from set A_C) whose ID is recorded in α_m, to simultaneously fulfil the requirement of having its CH selection index $\xi(\alpha_m)$ smaller than a set threshold ξ_{Th}. That is,

$$CH_{\text{Bkp}} = \underset{k \in \Theta_i}{\arg\min} \{\alpha_m \mid \xi(\alpha_m) \leq \xi_{Th}\} \tag{16}$$

With reference to (14) and (15) the threshold ξ_{Th} can be established. In (16) the threshold is selected amongst values recorded in set Ξ_{A_S}, depending on the choice of cluster member ID β_m, as

$$\xi_{Th} \doteq \xi(\beta_m) \quad m = 1, ..., N. \tag{17}$$

From Figure 3 it is important to notice how the choice of the threshold can drastically influence the terms under which the CH_{Bkp} is selected. Picking the cluster member ID β_m with small ordering index m, will result in adding more weight to the CH selection index ξ during the selection, because the resulting threshold will be very small. On the other hand, by employing a higher threshold, that is choosing a β_m with a large ordering index m, the weight of the decision making process is shifted to the cardinality degree. In this work a higher threshold ξ_{Th} is chosen to minimise the repercussions in terms of losing CMs after changing from CH to CH_{Bkp}.

B. Cluster Maintenance

The rest of the maintenance phase is described in Algorithm 2, which is designed to minimise cluster changes for every possible event, namely for the following situations:

- The CH leaves the network, that is the vehicle will turn at the next intersection.
- The CH is within the communication range of at least another CH.
- A CM loses connection with the CH.
- A new vehicle joins the network.

If a CH leaves the system, it will put its CH_{Bkp} in charge of the cluster. All the CMs in cluster Θ_i can therefore still hold onto the original cluster structure and avoid going through the clustering process again. In the case a CH_{i} can hear at least another CH_{j} but the backup cluster head of cluster Θ_i, $\text{CH}^{\text{i}}_{\text{Bkp}}$, is not in range of the other CH_{j}, then the $\text{CH}^{\text{i}}_{\text{Bkp}}$ will become the new CH_{i}, without the need of a new election. On the other hand, if both the CH_{i} and its $\text{CH}^{\text{i}}_{\text{Bkp}}$ lie within CH_{j} transmission range, the two CHs will merge. The CH with more CMs in its cluster will maintain its role whilst the other (with the minimum number of CMs) will become its CM. Lastly, if a new node joins the network or loses connection with the reference CH, it will undergo the CH selection procedure already explained in Algorithm 1.

Algorithm 2 Cluster Maintenance

```
for each CH_i do
    CH_i chooses the CH^i_Bkp using (16) and (17)
end for
if CH_i leaves system then
    CH^i_Bkp ← CH_i
end if
if CH_i is in range of another CH_j then
    if CH^i_Bkp is not in range of CH_j then
        CH^i_Bkp ← CH_i
    else
        merge cluster Θ_i and Θ_j
    end if
end if
if CM_i is not in range of CH_i then
    go to CLUSTER HEAD ELECTION
end if
if new vehicle k enters the system then
    go to CLUSTER HEAD ELECTION
end if
```

V. Performance Evaluation

Experimental simulations were conducted to assess the performance of our proposed clustering algorithm, SCalE. The performances of our proposed method are compared with the Highest-Degree and VMaSC methods. The former is commonly used for comparative purposes in the literature [12], [13], [14], it selects the vehicle with greater number of neighbours as CH. Therefore, this algorithm is characterised by a smaller number of CH and bigger cluster size. The VMaSC algorithm was proposed in 2016 in [11], it selects the vehicle with the lowest average relative speed in range as CH.

A. Mobility model

A Matlab implementation of the Gipps car following model and the Gipps lane-changing model [15], [16] (also used in the AIMSUN simulator) is employed in this work. The behaviour of each vehicle, in terms of speed or lane changing decision, is determined using information such as vehicle dimensions, current traveling speed, distance to the leading vehicle, acceleration and deceleration. A highway scenario of 8 lanes, 4 in each direction is implemented. The highway section is 6 km long and an additional side exit is placed at the 3 km mark for both directions, as seen in Figure 4. The side exit is accessible only to vehicles driving on or that move to (due to the lane changing model) the side lane. Vehicles are injected in

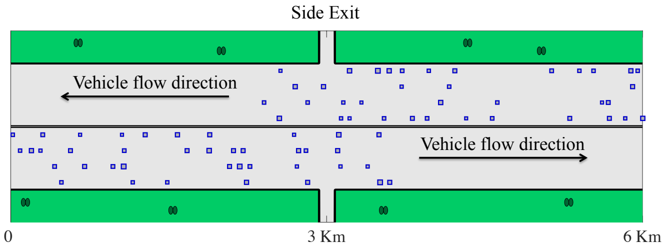

Fig. 4. Simulations scenario. Highway of 4 lanes for each moving direction. Length of road section is $6Km$ and 2 side exits are placed at $3Km$ to allow vehicles driving on or moving to (using the Gipps lane changing model) the side lane to leave the highway. Arrival rate of $\lambda = 5car/min$ for illustrative purpose only.

the system, at either end of the highway in Figure 4, following a Poisson process with arrival rate λ =30 veh/min. A network of 560 cars is monitored for 350 s. The probability that a vehicle on the side lane leaves the network at the side exit is $p = 0.7$. Vehicles can assume different sizes from 2 m to 7 m and their speed can vary in the range of 22 - 33 m/s.

B. Clustering performance criteria

The performance of a clustering algorithm can be measured by several metrics. In this work the following are used:

- *Average CM Lifetime* represents the average time a vehicle spends as a member of the same cluster and it is an important measure of the cluster stability.
- *Number of Leaving CHs* counts how many CHs leave the system at the side exit during the simulation time. Cluster stability is directly influenced by this metric since every time a CH leaves the system its CMs have to undergo a new CH election process. It is normalised by the highest value to allow relative comparison.
- *Number of CH Re-elections* is the total number of new CH elections that take place during the simulation. It represents the cluster stability and the additional delay suffered by vehicles due to re-elections. This metric is also normalised by the highest value.
- *Average Number of Reaffiliations* per vehicle is defined as the average number of times a vehicle starts or join a new cluster due to one of the following reasons: 1) a CH gets detached from its cluster, 2) a CM gets detached from its cluster, 3) a CH merges with a second CH. The value is an additional criteria used to establish the reliability of the cluster structure. This metric is then normalised by the highest value to allow relative comparison.

C. Performance Analysis

The number of CHs leaving the system at the side exit decreases with the communication range as shown in Figure 5. The graph shows that SCalE has the best performance, due to the tailored selection of the CH using the vehicle's behaviour information B_k. Furthermore, the use of a stable $\mathrm{CH_{Bkp}}$ with high coverage over the cluster can help reduce the number of vehicles losing contact with their CH, meaning the number

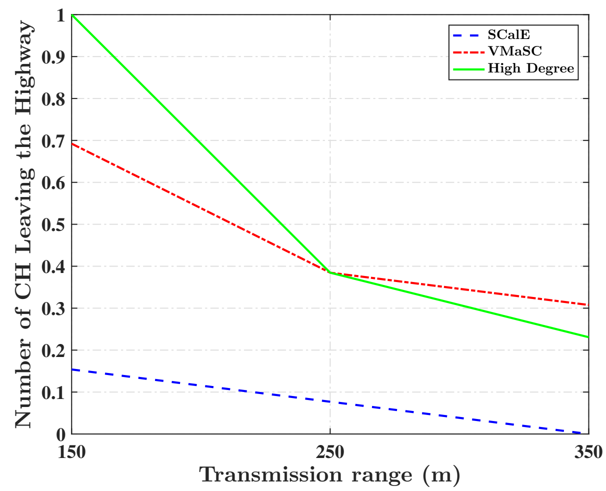

Fig. 5. Normalised number of CHs leaving the highway at the side exit

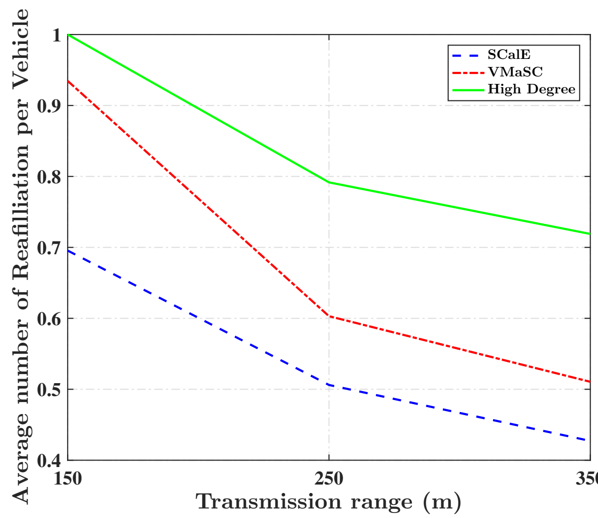

Fig. 6. Normalised Average number of cluster reaffiliations per vehicle

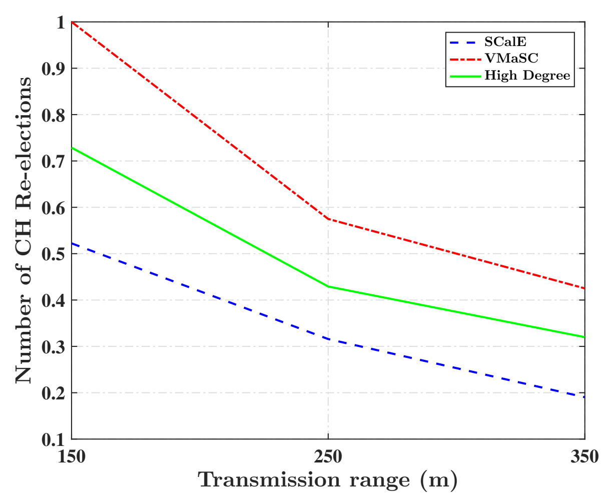

Fig. 7. Normalised average number of CHs re-elections

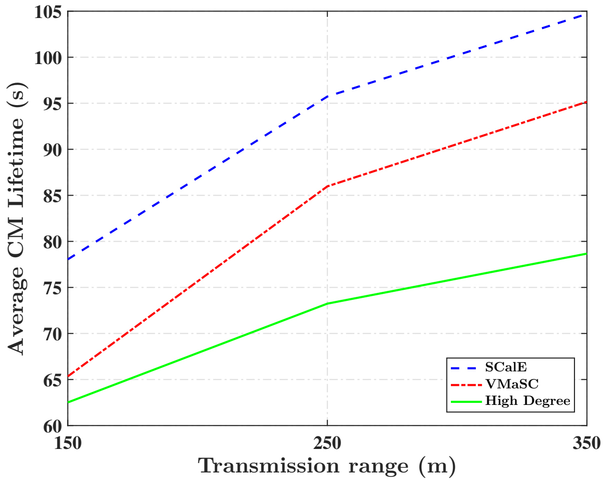

Fig. 8. Average cluster member lifetime

of reaffiliations can be reduced as Figure 6 indicates. Consequently the number of CH re-elections is also diminished as observed in Figure 7, allowing SCalE to outperform the Highest-Degree and VMaSC algorithms. Finally, Figure 8 shows that the average lifetime of a CM decreases with the vehicle's transmission range. It can be noticed that the proposed algorithm has better performance. This is demonstrated by the fact that the SCalE algorithm can select a stable CH and CH_{Bkp} capable of maintaining the cluster structure for longer than other algorithms.

VI. Conclusion

In this paper, we have proposed a Stable Clustering Algorithm for vehicular ad-hoc networks (SCalE), in order to improve the stability of the communication vehicles and facilitate efficient networking between vehicles and UAVs or cellular base stations. The clustering algorithm groups neighbouring vehicles into a cluster and selects two of them as the cluster head and backup cluster head, respectively. The stability of the cluster structures is achieved by the use of knowledge of the vehicle's behaviour in the cluster-head selection as well as the use of the backup cluster head to enable efficient maintenance of the cluster structure. Simulation results presented in this paper validate the SCalE algorithm under the challenging circumstances of working in a highly mobile environment. A performance comparison with Highest-Degree and VMaSC algorithms shows that SCalE is able to enhance the cluster stability in various performance metrics such as the average cluster member lifetime, the number of cluster heads leaving the system, the number of cluster head re-elections and the number of reaffiliations per vehicle.

Acknowledgment

This work was started by Giorgia Rossi during a research internship at Toshiba Research Europe in Bristol, U.K. In addition, Giorgia Rossi and Kin K. Leung would like to thank the U.K. Defence Science and Technology Laboratory (Dstl) for funding this research through the National U.K. PhD programme.

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