Pick the Right Guy: CQI-Based LTE Forwarder Selection in VANETs

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Abstract*—Periodical collection of data from vehicles inside a target area is of interest for many applications in the context of Intelligent Transportation Systems (ITS). Long Term Evolution (LTE) has been identified as a good candidate technology for supporting such type of applications – particularly for the non-safety domain. However, a high number of vehicles intermittently reporting their information via LTE can introduce a very high load on the LTE access network. In this context, the use of heterogeneous networking technologies can yield significant offloading of LTE – here, WLAN and Dedicated Short-Range Communication (DSRC) technology can support local data aggregation. In this paper, we propose an on-the-fly distributed clustering algorithm that uses both LTE and DSRC networks in the forwarder selection process. Our results clearly indicate that it is crucial to consider parameters drawn from both networking platforms for selecting the *right* forwarders. In particular, we show for the first time that relying on the Channel Quality Indicator (CQI) has a substantial impact. We demonstrate that our solution is able to significantly reduce the LTE channel utilization with respect to other state of the art approaches.

I. Introduction

Nowadays, modern vehicles are becoming an essential source of information in the context of Intelligent Transportation Systems (ITS), as well as urban sensing in general. They can be seen as information hubs [1] due to their increasing computing and storage capacity, but also as mobile sensors due to their mobility and growing number of on-board sensors. Allowing vehicles to communicate and exchange information among themselves makes them even more valuable, which is why intense work has been carried out in the last years by the research community and the automotive industry to enable vehicular networking [2]. These efforts led to the implementation of the Dedicated Short-Range Communication (DSRC) technology and to the development of such standards as IEEE WAVE [3] in the U.S. and ETSI ITS-G5 [4] in Europe.

Most of Inter-Vehicle Communication (IVC) research proposes DSRC as the main technology to be used for vehicular *safety* applications. One of the main motivations is the very low transmission delay (in the order of ms) required by these applications and satisfied by DSRC. Another reason is that DSRC operates on a dedicated spectrum (75 MHz in the United States and 50 MHz in Europe at 5.9 GHz frequency), which is specifically assigned for ITS. On the downside DSRC suffers from scalability issues. Also, in order to support centralized services and applications, additional gateways and hardware is needed, like Roadside Units. The deployment of such infrastructure is expensive [5]. Moreover, the technology itself is not yet widely available.

Long Term Evolution (LTE) has been identified as a good candidate technology for supporting *non-safety* applications [6], like urban sensing and traffic efficiency. These applications are generally delay tolerant and aim at improving the vehicle traffic flow, traffic coordination and assistance, as well as providing up-to-date locally relevant information bounded in space and/or time. The applications usually require intermittent collection of data from every vehicle roaming inside a target area. The collected information can contain kinematic data for traffic monitoring (e.g., vehicles' position, speed, direction of travel, time), technical and service data for vehicle monitoring, or environmental data for urban sensing. This information, known in the literature as Floating Car Data (FCD), needs to be periodically reported to a remote central server for processing. Of course, the granularity of the collected data and the reporting frequency depends on the target application type. In this context LTE offers high throughput, promises high penetration rate, and has the advantage of being already widely deployed. However, LTE has several drawbacks. First of all, it operates in a licensed spectrum, meaning that its performance and availability is highly dependent on the mobile and network operators. Also, in high density urban scenarios the periodic data transmissions from many vehicles can use a significant part of the LTE channels, possibly degrading the normal operation of traditional applications. In order to support the increasing amount of data traffic, LTE needs further upgrades, like decreasing the cell sizes, or adding more spectrum. All these upgrades are not for free, requiring additional investments from the network operators.

Optimizing the utilization of the LTE resources when periodically collecting information in vehicular networks is a challenging task. A typical approach aiming to solve this issue is the adoption of clustering mechanisms in multi-technology heterogeneous vehicular networks [7]–[13]. The main motivation for this is to use other technologies to offload the traffic from the cellular network. Generally, these clustering algorithms consist in selecting a subset of vehicles, named Cluster Head vehicles, to act as local *aggregators* and *forwarders* towards the cellular network. The forwarder election itself can be done either in a centralized [12] or distributed [7]–[10] fashion, while the aggregation inside each cluster is performed through IVC.

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The existing clustering algorithms for heterogeneous vehicular networks rely on DSRC as the main technology for IVC and cluster creation, while LTE is used by the selected forwarders to periodically report the aggregated information to the remote server. In this context, the parameters used in the forwarder selection process become very important. The number of DSRC neighbors is the most used parameter when the objective is to minimize the LTE channel utilization. The reason is that the DSRC connectivity parameter helps in minimizing the number of forwarders accessing the LTE channel, hence reducing the packet header overhead.

Although the DSRC connectivity parameter cannot be ignored, as we further show in this article, using it as the only parameter for electing forwarders turns out to be suboptimal. In this paper we identify another relevant parameter that has to be used in the forwarder selection process in order to further reduce the LTE channel utilization, namely the Channel Quality Indicator (CQI) in the LTE uplink [14]. We prove that for choosing the *right* vehicles to act as forwarders, both DSRC connectivity and CQI parameters have to be used in the election process, as well as some jitter [15] – a randomly varying timing that aims at preventing vehicles from simultaneous transmissions. To this purpose, we propose a distributed clustering algorithm that combines the above mentioned parameters. The proposed solution does not require any a priory knowledge (e.g., road intersection coordinates) or dedicated infrastructure.

Our main contributions can be summarized as follows:

- We introduce a new parameter in the forwarder election process, namely the CQI in the LTE uplink, and prove that a proper combination of the DSRC connectivity, CQI, and jitter is able to further reduce the LTE channel utilization with respect to current state of the art approaches based only on the DSRC connectivity parameter.
- We propose an on-the-fly distributed clustering algorithm with forwarder selection, named On-the-Fly Clustering (OFC), which exploits the DSRC technology to significantly decrease the LTE channel utilization.
- Our results confirm the relevance of the new introduced parameter and show that OFC outperforms other state of the art approaches in terms of LTE Resource Block (RB) utilization [16].

II. Related Work

LTE has been identified as a potential access technology able to support vehicular communications [6], [17], [18]. There are several reasons why LTE is suitable. First of all, it has the benefit of an already pre-deployed infrastructure, which offers wide area coverage and supports high mobility. Secondly, the market penetration rate of LTE is expected to be higher compared to other communication technologies, since the LTE technology is already integrated in common user devices, like smartphones, tablets, and smartwatches. Moreover, many vehicular applications can migrate to these devices.

Araniti et al. [6] provide an extensive survey on the state of the art of LTE and its capability to support vehicular applications. Mangel et al. [17] analyze the usability of LTE for vehicular safety communication at intersections, comparing them with DSRC. They conclude that even if LTE seems able to support periodic delivery of beacon messages, its performance in terms of awareness update rate and latency is inferior with respect to DSRC. On the other hand, the latency and reliability requirements are not so strict for non-safety applications. Yet, the information generated by a high number of vehicles can heavily load the uplink channel, preventing the normal operation of traditional human-to-human traffic. Ide et al. [18] propose a channel sensitive probabilistic transmission scheme in order to reduce the LTE channel load. Their algorithm reduces the number of forwarders, but does not guarantee an exhaustive collection of data.

DSRC has been proposed as the main technology for IVC. The primary motivation is to ensure safety on the roads by enabling Vehicle-to-Vehicle communication and cooperative awareness. The latter is usually obtained through periodic exchange of *beacon* messages. Beacons contain vehicle's position, velocity, direction of travel, number of current DSRC neighbors, and other basic information. They are periodically broadcast from either vehicle to its neighbors, so that every vehicle at every time instant has an updated list of its one-hop neighbors. These messages are referred to as Cooperative Awareness Messages (CAMs) [19] or Basic Safety Messages (BSMs) [20].

Among the advantages that DSRC offers we can identify low message delays, decentralized architecture, and localized network load. However, to support non-safety applications, DSRC needs additional hardware and infrastructure deployment, like Roadside Units. Moreover, the technology currently is not yet widely deployed, meaning that at least in the initial stage DSRC needs to be supported by other existing communication technologies.

To cope with the limitations that both LTE and DSRC have, the research community is shifting towards heterogeneous vehicular networking approaches [7]–[13]. The idea is to deploy both technologies to vehicles and road, and to exploit the benefits from each technology. A common paradigm is to use the cooperative awareness enabled by DSRC to create clusters of vehicles having common features (e.g. proximity, travel direction, speed, connectivity). A complete taxonomy on clustering in vehicular networks is proposed by Bali et al. [21]. There a comprehensive analysis of existing proposals in literature is provided, as well as a detailed discussion for each category of clustering, including challenges and future directions.

Non-safety applications usually require periodic collection of data from vehicles inside a target area. Various applications have different requirements in terms of accuracy of the reported information. For instance, Ide et al. [7] focus on a traffic forecast application where neighboring vehicles have similar information. Based on this assumption, elected forwarding vehicles perform local aggregation and compression before sending the information to the remote server via LTE. The upper bound of the amount of compressed data is modeled as a square root function of the number of uncompressed data units. In many non-safety applications the information cannot be compressed, meaning that data from every single vehicle must be gathered. In this case the aggregation consists in concatenating the payloads gathered from the DSRC neighboring vehicles.

The target application has a strong impact on the decision of what parameters to consider in the clustering mechanism. Many applications aim at obtaining cluster stability, meaning that the vehicles' position, speed, and driving direction are the most critical parameters. Other applications focus on minimizing the LTE channel utilization while periodically collecting data from vehicles. In this case DSRC connectivity becomes predominant, since the main objective is to collect data from the whole vehicle network, while minimizing the number of forwarders and maximizing the local aggregation.

Stanica et al. [8] identify this as to be equivalent to the Minimum Dominating Set problem in graph theory, known to be NP-complete. They propose three heuristics for the election of Cluster Head vehicles in a heterogeneous LTE/DSRC vehicular network: Degree-Based, Degree-Based with Confirmation, and Reservation-Based. These algorithms are evaluated in terms of *system gain*, defined as the fraction of vehicles that do not have to access the cellular infrastructure when data is offloaded through DSRC communication. However, this metric does not directly measure the utilization of the LTE channel. In this article we are actually focusing on measuring the Resource Block utilization in the LTE network. Moreover, Stanica et al. [8] assume a simple unit disk model for IVC connectivity, where two vehicles can communicate whenever their distance is below a threshold R, which is a non-realistic assumption. Also, all heuristics presented above are trying to minimize the number of forwarders by relying only on the DSRC connectivity parameter.

In this article we show that considering the CQI [14] in the LTE uplink and some jitter in addition to the DSRC connectivity, and properly combining them in the forwarder selection process can yield significant offloading of LTE.

III. LTE Channel Quality Indicator

One of the key features of LTE is the possibility of selecting the downlink/uplink transmission configuration and related parameters depending on the current channel condition, including the interference situation [22]. The instantaneous channel quality, namely CQI, is provided periodically or aperiodically by the terminals to the eNodeB. The eNodeB makes up decisions on resource allocation based on the terminal CQI information. *Periodic* CQI reports can be transmitted on the Physical Uplink Control Channel (PUCCH) or Physical Uplink Shared Channel (PUSCH), while *aperiodic* reports can be transmitted only on PUSCH.

In LTE, CQI provides quantized indication of the highest modulation and coding scheme that, if used by the eNodeB, lets the User Equipment (UE) demodulate and decode the transmitted downlink data with a maximum block error rate of 10 %. However, the CQI is only a recommendation, meaning that the eNodeB does not need to necessarily use it. The reason is that the eNodeB has to consider also other information when allocating resources. For instance, if the UE needs to transmit only a small amount of data, then there is no need to select a very high data rate, because a small number of RBs with robust modulation is sufficient. There are 15 different CQI values, ranging from 1 to 15. The higher the CQI value reported by the UE, the richer the modulation scheme (from QPSK to 64QAM) and the bigger the coding rate used by the eNodeB to improve the efficiency as much as possible.

There is no explicit description in the standard documents of the mechanism by which the CQI is calculated, but it is known that the Signal to Noise Ratio (SNR) and/or Signal to Interference plus Noise Ratio (SINR) factors play important roles in the CQI computation. How these factors should be used and whether there are any other factors that should be involved is not well defined. Our estimation of the CQI is based on the work of Virdis et al. [23], which uses a mapping table of measured block errors to determine the CQI based on a given SINR value.[1] The SINR is computed as

$$\mathrm{SINR} = \frac{P_\mathrm{s}}{\sum_i P_i + N} \ , \tag{1}$$

where P_s is the power received from the serving eNodeB, P_i is the power received from the interfering eNodeB i, while N is background Gaussian noise. The received power P is computed as

$$P[\mathrm{dBm}] = P^\mathrm{tx}[\mathrm{dBm}] - L_\mathrm{P}[\mathrm{dB}] - L_\mathrm{S}[\mathrm{dB}] - L_\mathrm{F}[\mathrm{dB}] \ , \tag{2}$$

where P^tx is the transmit power, L_P is the path loss [24], while L_S and L_F represent the attenuation due to slow and fast fading, respectively.

Since the main idea behind the clustering algorithms in heterogeneous vehicular networks is to properly choose the forwarding vehicles, we think that the CQI has to be used in the selection process. Not using the CQI parameter can lead to the election of forwarding vehicles having a poor CQI. For such forwarders, which have to send a high amount of aggregated information via LTE, the eNodeB wastes plenty of resources, leading to an inefficient utilization of the LTE channel. The waste of resources comes from the modulation and coding scheme that the eNodeB chooses according to the reported CQI. This means that a vehicle with a lower CQI value encodes much less information in one RB than a vehicle having a higher CQI.

IV. On-the-Fly Clustering

We first present a sample application used in our study, showing a simple LTE-based data collection algorithm, and then propose an on-the-fly distributed clustering algorithm with forwarder selection, named OFC, that uses both LTE and DSRC technologies to collect data in a heterogeneous vehicular network.

[1] http://github.com/inet-framework/simulte

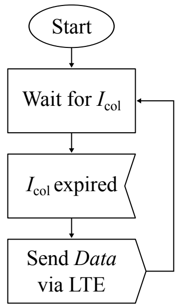

Figure 1. PureLTE data collection algorithm.

A. *Traffic monitoring application*

We consider a traffic monitoring system as use case example for our study, but any other application that needs periodic exhaustive collected information is relevant. We assume that every vehicle inside the target area has LTE communication technology available on board. The application itself consists in periodically reporting FCD messages via LTE to the traffic monitoring system server. The updating frequency, which is common to all vehicles, is decided by the traffic monitoring system and is set up in the collection interval parameter (I_{col}) by every vehicle (i.e., when the application starts, it can immediately send a request to the remote server via LTE asking for the desired reporting frequency).

A simple algorithm that periodically collects FCD messages in such a scenario is presented in Figure 1. We will further refer to this approach as PureLTE. Basically, whenever the application starts, it periodically schedules a time-out event, named I_{out}, equal to the collection interval parameter. When the time-out expires, the application sends a *Data* message via LTE to the traffic monitoring system server containing updated information about the vehicle itself. Notice that a *Data* message can contain one or more FCD messages. In this particular case *Data* consists of only one FCD message created by the transmitting vehicle itself, since no IVC communication is present. The transmissions are not synchronized among different vehicles. The only common information that must be known to all vehicles is the parameter I_{col}.

Although this approach is very simple, it implies that every vehicle has to periodically report its FCD, which can introduce a high load over the LTE channels, especially in the case of urban scenarios with high vehicle density [25]. Considering that many different vehicular applications, as well as all regular LTE traffic, will have to share the same limited LTE bandwidth provided by the mobile and network operators, this issue becomes even more critical.

B. *OFC algorithm*

The FCD collection application assumes each vehicle maintains a Local Data Base (LDB) where the relevant information about the vehicle itself and about its current neighbors is stored. A background exchange of one hop messages on DSRC keeps the LDBs up to date. When the time comes for sending a report, the elected forwarding vehicle reads its current LDB content and sends it to the remote server. An example of such a process is already envisaged explicitly by ETSI standards, where the CAM exchanged among neighboring vehicles and the Local Dynamic Map [26] data base are defined to maintain vehicle awareness of the surrounding vehicular traffic environment. We do not pursue the details of the LDB maintenance further, since this has been widely investigated in the literature (e.g., see [27][28]).

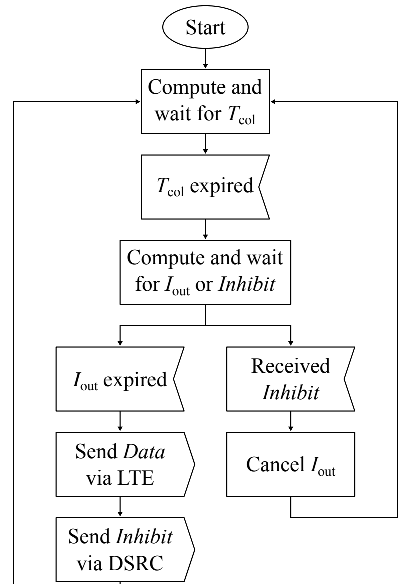

Figure 2. OFC data collection algorithm.

The main idea behind OFC is to allow only a subset of vehicles, named *forwarders*, to report via LTE their own, as well as their one hop neighbors' Floating Car Data. These forwarders are dynamically selected during every collection interval. The selection process itself is based on synchronized selection phases and takes into account the current number of DSRC neighbors, the CQI in the LTE uplink information, and a uniformly distributed random jitter. OFC operation is highlighted in Figure 2. Unlike the PureLTE approach, where no synchronization is needed since no IVC is present, with OFC the time instance when the collection interval starts must be the same for all vehicles. Although the forwarder selection mechanism is performed locally, it has to start at the same point in time for all vehicles, since the considered parameters have to refer to the same time instance. Hence, every time when the applications starts, besides initiating the beaconing process, it finds the next collection interval according to

$$T_{\text{col}} = T_{\text{cur}} - (T_{\text{cur}} \bmod I_{\text{col}}) + I_{\text{col}} \tag{3}$$

where T_{col} is the point in time when the collection interval starts, T_{cur} is the current time instance (i.e., we assume every vehicle has a GPS on board which can provide the current time) and I_{col} represents the collection interval span.

Upon collection interval starting, every vehicle computes its own sending time T_{send} according to

$$T_{\text{send}} = T_{\text{col}} + I_{\text{out}} \tag{4}$$

where the time-out interval I_{out} is given by

$$I_{\text{out}} = I_{\text{col}}\left(\alpha X + \beta Y + \gamma Z\right) \ , \tag{5}$$

Here α, β, and γ are non-negative weights chosen so as that $\alpha + \beta + \gamma = 1$, and $\alpha, \beta, \gamma \in [0, 1]$. X, Y, and Z represent the DSRC connectivity, the CQI in the LTE uplink, and the jitter respectively and are computed as

$$X = 1 - \frac{N_{\text{cur}}}{N_{\text{max}}} \tag{6}$$

$$Y = 1 - \frac{Q_{\text{cur}}}{Q_{\text{max}}} \tag{7}$$

$$Z = \mathcal{U}(0, 1) \ , \tag{8}$$

where N_{cur} and Q_{cur} represent the current number of one hop DSRC neighbors and the current CQI in the LTE uplink of a generic vehicle (in case of subband-level CQI reporting, the average value over all subbands is considered), while N_{max} and Q_{max} are the corresponding maximum values. Notice that Q_{max} refers to the maximum CQI index, which is globally known to all vehicles, while N_{max} is locally computed by every vehicle. In particular, N_{cur} is included in the beacon exchange process, meaning that every vehicle knows the number of neighbors for each one of its one-hop DSRC neighbors. At this point a vehicle can compute N_{max} by finding the maximum N_{cur} value among all its neighbors.

It is important to study the impact that each of the three considered factors has. This is why we introduce three weight parameters, namely α, β, and γ, which are needed for tuning the considered factors (see Section V-B). According to Equation (5), vehicles having a higher number of DSRC neighbors and a better CQI in the LTE uplink are scheduled for transmission first. Vehicles whose time-out expire, become forwarders and prepare their *Data* message to be sent to the traffic monitoring system by reading their LDB. Immediately after sending the *Data* message via LTE, a forwarder has to inform its neighbors by broadcasting an *Inhibit* message over the DSRC network, containing the identifiers of all vehicles whose FCD was enclosed in *Data*. If a vehicle waiting for its time-out to expire receives an *Inhibit* message, it checks whether its identifier is present. If this is true, then it immediately cancels the time-out I_{out}, aborting its scheduled transmission.

Notice that an inhibited vehicle can be in the transmission range of more than one forwarder, meaning that multiple copies of the same FCD message can be sent to the server, increasing the LTE channel utilization. A simple solution is to enable 2-hop inhibition awareness, meaning that whenever a vehicle is inhibited, it has to broadcast a notification message to inform its neighbors about the inhibition, so that other potential forwarders from its neighborhood can avoid sending its FCD message again. Yet, such solution could lead to the congestion of the DSRC channel in high vehicular density scenarios.

We propose instead a mechanism that takes advantage of the already existing beacon exchange process. In particular, we extend the beacon messages sent in background by adding a flag, named *SentFlag*. At the beginning of each collection cycle, vehicles set their *SentFlag* to FALSE. As soon as a vehicle A receives an inhibition message from a neighbor, announcing that the neighboring vehicle has reported A's FCD to the remote server, A turns its flag to TRUE. Whenever a vehicle node updates the application information by sending a message to its neighbors, it includes the current value of its *SentFlag*. As a consequence, updates of the application data sent by the inhibited vehicle A every I_{LDB} seconds carry the flag set to TRUE and cause the relevant information to be updated in the LDBs of A's neighbor vehicle nodes. If any of those neighbors reports their *Data* to the remote server, it will exclude A's FCD. The effectiveness of the *SentFlag* mechanism depends on the ratio between the time interval I_{LDB} of the background application LDB periodic update and the data collection time interval I_{col}: the smaller $I_{\text{LDB}}/I_{\text{col}}$, the more effective the *SentFlag* mechanism.

V. Performance Evaluation

We first present our simulation scenario, then we evaluate the influence of DSRC connectivity, CQI in the LTE uplink and randomness parameters, and finally, we compare our proposed solution with the PureLTE data collection algorithm, as well as with a baseline solution that selects forwarders based on the DSRC connectivity parameter only.

A. Simulation setup

For evaluating the proposed algorithms we use *Veins LTE* [29], an LTE extension of the well-known open source vehicular network simulator *Veins*[2] [30]. A realistic Manhattan grid scenario is considered for our simulations, created using the real Manhattan downtown road and building dimensions. The Krauss vehicular mobility model is used, along with the random trips traffic flow origin-destination model. Although the vehicular mobility is simulated over a larger area, we enclosed the observed region to a smaller target area to avoid border effects. Also, we use the free-space path loss ($\alpha = 2$) with obstacle shadowing models for DSRC and urban macro path loss [24] with Jakes multi-path fading models for LTE.

We assume LTE coverage is available inside the target area. All vehicles are equipped with DSRC and LTE wireless network interfaces, while the decision whether to send a packet on one interface or on another is taken at the application layer. Considering that most likely the mobile operators will dedicate only a small portion of bandwidth to vehicular applications, for our analysis we assume a bandwidth of 3 MHz (15 available RBs). Since different traffic monitoring systems, but also other applications, might have particular requirements in terms of data reporting frequency, we analyze and compare the performance of the three considered solutions with respect to different collection intervals.

All simulations are run for 300 s preceded by 200 s of warmup time. Every simulation is repeated 25 times with inde-

[2]http://veins.car2x.org

Table I
SIMULATION PARAMETERS

Parameter	Value
Simulated area	580 m × 490 m
Average number of vehicles	133–195
Average density (veh/km/lane)	4–6
Simulation duration	300 s
IVC technology	IEEE 802.11p
IVC maximal transmit power	20 mW
DSRC beacon frequency	5 Hz
Payload length	400 B
I_{col}	4–20 s
Number of available RBs	15
LTE scheduler	MAXCI
UE transmission power	26 dBm
eNodeB transmission power	45 dBm

pendent random number seeds. The most relevant simulation parameters are displayed in Table I.

B. Studying the influence of DSRC connectivity, CQI, and jitter

Our intention is to include the most relevant parameters describing the communication capabilities. We can notice that there are three different parameters that can affect the performance of our algorithm: the number of DSRC neighbors, the CQI in the LTE uplink and the jitter. What we are interested in is to assess the influence of CQI and jitter parameters when adding them to the DSRC connectivity.

To this purpose, we investigate the performance of our heterogeneous data collection algorithm in terms of RB utilization for different values of α, β, and γ, ranging from 0 to 1 with a 0.05 step, for a fixed collection interval $I_{\text{col}} = 10$ s. The RB utilization is computed as the percentage of RBs allocated to all vehicles inside the target area sampled every ms and averaged over the observed time interval. Since the above mentioned parameters are not independent, we show only the values of β and γ, while $\alpha = 1 - \beta - \gamma$.

The results of our study are shown in Figure 3. The x-axis represents the parameter β (i.e., the influence of CQI in the LTE uplink), while the y-axis shows the percentage of the RB utilization. Because of visibility reasons we choose to plot only three values of γ, namely $\gamma = 0.2$, $\gamma = 0.5$, and $\gamma = 1$, although we simulated the entire range from 0 to 1. However, the other curves show similar behaviors.

The first thing that can be noticed is that the LTE channel utilization is higher for low values of β, meaning that the CQI parameter must be considered with a proportion of at least 10 % when designing clustering algorithms for reducing the RB utilization. Also, a slight increase can be seen for $\beta > 0.7$, which means that increasing too much the influence of the CQI in the LTE uplink and decreasing the weight of other parameters is not the best solution. The utilization of the LTE channel is minimized for $0.1 < \beta < 0.7$. We can notice that, if choosing an influence factor for the CQI inside this range, the RB utilization can be decreased to 70 % with respect to the case when not using the CQI at all ($\beta = 0$).

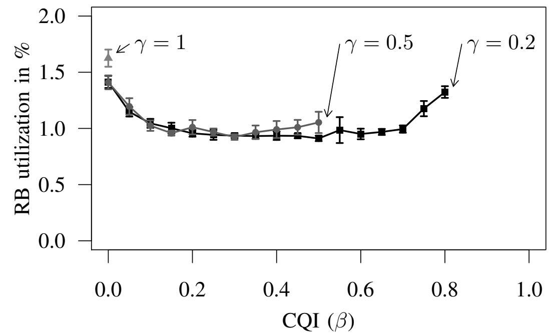

Figure 3. OFC performance in terms of RB utilization as a function of β for different values of γ.

When looking at the jitter influence, we can see that varying γ between 0.2 and 1 does not affect too much the performance. In fact, we can notice that the curves overlap and their shapes are similar. However, according to our results (data not shown), not using jitter at all (i.e., $\gamma = 0$) increases the RB utilization up to 400 % with respect to $\gamma = 0.2$. This confirms the need of using at least some jitter. Moreover, the curve shape for $\gamma = 0$ matches the other ones plotted in Figure 3, meaning that even in this case the CQI parameter helps in decreasing the RB utilization. According to these results, for the comparative performance evaluation in the next section we choose the following weight values: $\alpha = 0.3$, $\beta = 0.5$, and $\gamma = 0.2$.

C. Comparative performance evaluation

The aim of this evaluation is to measure the utilization of the LTE uplink channel, the introduced overhead, and the delay of the reported information when varying the required collection interval. To this purpose, the considered algorithms are evaluated in terms of RB utilization in the LTE uplink, message duplicates ratio, and inter-arrival time of the reported FCD messages. The duplicates ratio is calculated as the number of duplicate messages over the number of total received messages. The inter-arrival time is measured as the time difference between two consecutive FCD message receptions at the server side belonging to the same vehicle.

We evaluate our proposed OFC algorithm and compare its performance with PureLTE, as well as with the following baseline state of the art solution, hereafter referred to as Baseline. Current state of the art solutions consider the DSRC connectivity as the main parameter in the clustering mechanism. OFC can be easily turned into this baseline algorithm by setting $\beta = 0$ (i.e., not using the CQI parameter at all). By doing so we end up having a heuristic which is minimizing the number of forwarders by selecting those vehicles with the highest number of DSRC neighbors. Notice that we still keep $\gamma = 0.2$ (i.e., jitter) to reduce simultaneous transmissions and obtain a fair comparison with OFC.

The mean RB utilization is depicted in Figures 4 and 5. We can notice that OFC is able to decrease the channel utilization to 25 % with respect to PureLTE and to 75 % with respect to Baseline. For PureLTE the high channel utilization is due to the

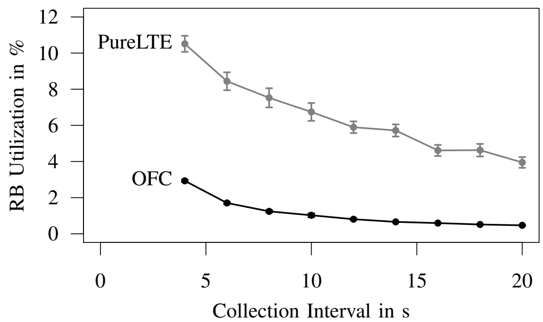

Figure 4. The RB utilization as a function of the collection interval for OFC and PureLTE.

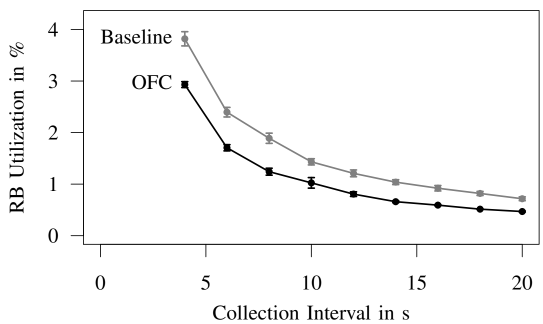

Figure 5. The RB utilization as a function of the collection interval for OFC and Baseline.

large number of vehicles accessing the channel and requesting resources. Although Baseline is reducing the number of vehicles accessing the channel by electing forwarders and performing aggregation, the RB utilization is still higher with respect to OFC. This is due to the fact that Baseline does not consider the CQI of the elected forwarders, meaning that these vehicles send more aggregated information while having a possibly very bad CQI, wasting much more resources with respect to OFC.

The relatively low RB utilization levels displayed in Figures 4 and 5 are due to the low vehicular density used in our simulations. Nonetheless, the results presented in these figures also show how the DSRC technology can significantly help in decreasing the LTE channel utilization, confirming its efficiency for *non-safety* applications. To achieve an important reduction in terms of RB utilization, DSRC connectivity must be properly combined with CQI in the LTE uplink and jitter parameters.

In Figure 6, we display the mean duplicates ratio for different collection intervals. We can notice that both OFC and Baseline introduce duplicates. This is related to the DSRC network topology and can be explained by the *network assortativity* phenomenon [31] from complex network theory, which implies that directly connected nodes (i.e, nodes in the same neighborhood) are likely to have similar degree levels. Also, it can be noticed that OFC and Baseline increase the duplicates ratio for lower collection intervals, meaning that more information is being sent to the server. This confirms the fact that the inhibition mechanism is more efficient for smaller $I_{\mathrm{LDB}}/I_{\mathrm{col}}$ ratios. Another interesting observation is that Baseline

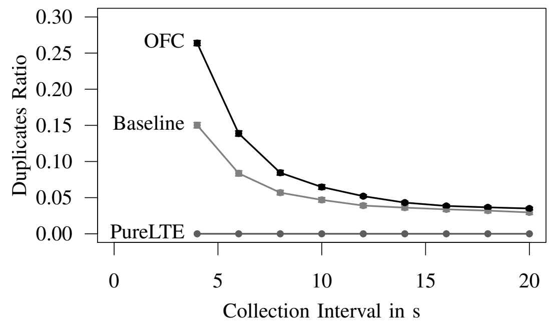

Figure 6. The duplicates ratio as a function of the collection interval for OFC, PureLTE, and Baseline.

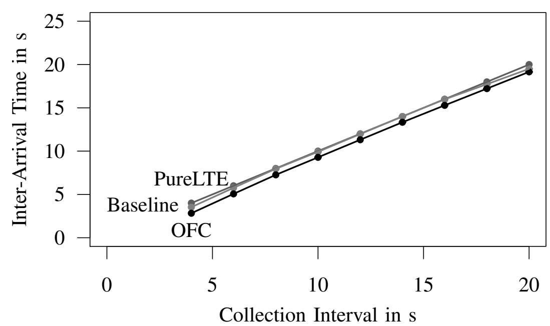

Figure 7. The inter-arrival time as a function of the collection interval. for OFC, PureLTE, and Baseline

induces less duplicates than OFC. This is because Baseline gives priority to vehicles having more DSRC neighbors in the forwarder selection process, thus minimizing the number of forwarding vehicles. However, since OFC tends to elect as forwarders those vehicles with a better CQI in the LTE uplink, it is still able to utilize less resources with respect to Baseline.

Another metric of interest is the FCD message inter-arrival time at the server side. In fact, a traffic monitoring system needs periodic updates from every vehicle roaming inside the target area to be able to accurately estimate the current road traffic condition. In Figure 7, we show the FCD message inter-arrival time for the three considered algorithms as a function of the collection interval. Clearly, the ideal case is given by the PureLTE algorithm, since every vehicle's reporting frequency is exactly the same as the requested data updating frequency by the traffic monitoring system server.

The story is slightly different for OFC and Baseline, where the reporting times are decided at every collection interval. However, from Figure 7 we can notice that the inter-arrival time curves for both OFC and Baseline follow the same trend and are very close to PureLTE, meaning that they are as efficient as PureLTE. The only difference is that, because of the duplicates introduced by OFC and Baseline, the information is seen on average a little bit more often at the server side with respect to the expected reporting frequency.

VI. Conclusion

In this paper, we show that the DSRC technology can significantly help in reducing the LTE channel utilization for non-safety applications that require intermittent collection of data. This is generally achieved through clustering mechanisms that select a subset of vehicles in charge of aggregating and sending the information to a remote server via LTE. We show that the DSRC connectivity parameter, which is the most commonly used criterion in the literature for selecting such vehicles, turns out to be suboptimal. Moreover, we show that a previously ignored aspect, namely the quality of the LTE channel, has a significant impact on the utilization of the LTE Resource Blocks. We prove that it is essential to use both DSRC connectivity and CQI parameters to further decrease the utilization of the LTE channel. In particular, the RB utilization decreases to 70 % when combining both parameters with respect to the case when using only one of them.

As a case study, we consider a simple traffic monitoring system that requires periodic collection of information from vehicles roaming inside a target area. We propose an on-the-fly distributed clustering algorithm with forwarder selection, named OFC, that considers the DSRC connectivity, the Channel Quality Indicator in the LTE uplink, and a randomly varying timing (i.e., jitter) as the main parameters in the forwarder selection process. Our results show that with a proper combination of the three above mentioned parameters in OFC, we are able to reduce the LTE channel utilization to 25 % with respect to a pure LTE-based data collection algorithm and to 75 % with respect to a baseline state of the art approach.

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