Achieving Data Utility Fairness in Periodic Dissemination for VANETs

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***Abstract*—In addition to safety, Vehicular Ad-hoc Networks (VANETs) enable the development of new information-rich applications that disseminate relevant data to vehicles. One key challenge in such networks is to use the available bandwidth efficiently when there is: (i) a short connectivity time due to the rapidly changing road environment, and (ii) bandwidth congestion due to continuous collection and dissemination of data. Numerous solutions were proposed to alleviate bandwidth congestion by using transmission power and beaconing rate control. However, the reduction of data messages transmitted by using priority-based *data selection* mechanisms has not been fully explored. In this work, we propose a periodic data dissemination protocol for non-safety applications which distributes data utility *fairly* among vehicles with conflicting data interests. Furthermore, given a defined maximum network load allowed, only the least relevant data is suppressed. Fairness is achieved using the concept of Nash Bargaining from game theory. Simulation results show that our approach leads to an efficient bandwidth utilization in terms of utility per message received and higher fairness index compared with other approaches.**

Keywords: Vehicular Ad-hoc Networks (VANETs), Vehicular Sensor Networks (VSNs), Data Dissemination

I. INTRODUCTION

Vehicular Ad-hoc Networks (VANETs) enable the development of new applications not only safety-related but also information-rich applications that can provide convenience and comfort to drivers and passengers [1]. In such networks, also referred to as Vehicular Sensor Networks (VSNs), vehicles rely on diverse built-in sensors to continuously gather, process, and disseminate relevant sensor data. For non-delay sensitive applications such as traffic monitoring, this dissemination can be accomplished by means of periodic broadcast with longer intervals compared to safety beaconing [2]. Periodic dissemination is especially suitable to dynamic scenarios, since there is no need for changing the protocol's operation mode to suit the current environment [3].

One key challenge in such networks is to use the available bandwidth efficiently when there is: (i) a short connectivity time due to the rapidly changing road environment and (ii) bandwidth congestion due to continuous collection and dissemination of data. Especially with regard to bandwidth congestion, numerous solutions were proposed with focus mainly on transmission power and beaconing rate control, as discussed in [4]. A complementary approach not often explored is to use the available bandwidth more efficiently through priority-based *data selection* mechanisms. With such mechanisms, data messages with high *utility* (relevance) are selected and broadcast to interested vehicles. However, one important challenge arises when considering conflict of data interests between vehicles depending on their current context. For example, two vehicles moving in opposite directions may be potentially interested in each other's data, since one holds data related to the destination of the other.

In this work, we address the problem of selecting data in a road environment where vehicles have conflict of data interests. Our contribution lies in presenting a data dissemination protocol that aims to distribute data utility fairly over vehicles, which we refer to as FairDD: *Fair D*ata *D*issemination. FairDD disseminates data through periodic data messages according to a defined application cycle and provide means for keeping the network load under a defined value by suppressing only the least relevant data messages.

The remainder of this paper is organized as follows. In Section II, relevant related works are outlined. Section III details the functioning of FairDD. The validation of FairDD is presented in IV. Finally, Section V concludes this paper.

II. RELATED WORK

Among the earliest works proposing the use of application utility for data selection are [5], [6]. In [5], authors focus on congestion control and packet forwarding in VANETs, whereas scalability issues are addressed in [6]. In both solutions, vehicles select data with the goal of maximizing the total utility gained by all vehicles in the neighborhood regardless of how much they profit individually. Differently, authors in [7] introduce a protocol that allows content to remain available in areas where vehicles are most interested in it. In [3], the message utility and channel quality are used to adapt the rate of beacons in non-safety applications.

One key aspect missing in these works is the consideration of utility fairness when vehicles have conflicting interests. Although in [8] authors introduce the concept of application-utility-based fairness, their focus is on controlling flow rates in time-constraint data traffic. Similar to our work is [9]. However, the data selection considered is restricted to only pairs of vehicles. In our work, we go one step further and present a generalized and fully distributed approach for utility data selection suitable for broadcasting communication.

III. FAIRDD

FairDD aims to achieve a *fair* distribution of data utility throughout the network while keeping the network load under a defined level. FairDD consists of two main components: (i) a distributed fair data selection mechanism and (ii) a synchronized suppression mechanism to cancel only the least relevant data messages.

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A. Utility Function

For a given application, the utility of a data message refers to the benefit that a vehicle can have by receiving that message. A message utility is calculated based on the current level of "interest" that a vehicle has in the message content depending on the vehicle's current context. For instance, if a message contains information about the vehicle's final destination, the application may consider giving a high utility to this message. However, from the perspective of another vehicle moving towards a different destination, the same information might be considered almost irrelevant. We classify this contextual knowledge into the following categories:

- ***Mobility context***: ranges from the complete route of a vehicle to the vehicle direction, speed, mobility history, etc.
- ***Data context***: includes the priority of the data message, age, geographical region, etc.

This contextual information can be weighted in a function which attributes a value u_{ij} to each data message m_j in view of vehicle v_i. The normalized utility value is given by:

$$u_{ij}(\alpha_1 z_1^i(m_j), \alpha_2 z_2^i(m_j), ..., \alpha_l z_l^i(m_j)). \tag{1}$$

where $z_k^i \in [0,1]$ with $k = 1, 2, ..., l$ are the functions for each type of contextual information k for vehicle i weighted by parameters α_k. The application is responsible for defining how these functions are combined in u_{ij}.

B. Data Selection

To achieve utility fairness in the neighborhood, we propose a distributed data selection mechanism that considers the individual interests of vehicles. FairDD relies on the Nash Bargaining [10] solution from game theory. This solution achieves a compromise between fairness and efficiency. Fairness refers to the symmetry of utility distribution among vehicles and efficiency refers to the total utility distributed.

Let U be utility matrix for h vehicles and n data messages,

$$U = \begin{array}{c c} & \begin{array}{cccc} m_1 & m_2 & \dots & m_n \end{array} \\ \begin{array}{c} v_1 \\ v_2 \\ \vdots \\ v_h \end{array} & \begin{pmatrix} u_{11} & u_{12} & \dots & u_{1n} \\ u_{21} & u_{22} & \dots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{h1} & u_{h2} & \dots & u_{hn} \end{pmatrix} \end{array}. \tag{2}$$

where u_{ij} is given by (1). In matrix U, the utility value for each pair (v_i, m_j) is given. There are n distinct data messages to be sent in the neighborhood. For a message to appear in U, there is at least one vehicle that has not received it yet. If vehicle i already has message j, then $u_{ij} = 0$.

One main feature of FairDD is that we take into account the accumulated utility c_i of each vehicle i. In this way, a vehicle that gained more in previous opportunities will have a lower priority to increase its c_i in the next data exchange. Nevertheless, since the communication is broadcast-based, such vehicle might still receive non-zero utility. Another property of c_i is that it continually changes depending on the current context of i. A change of context might lead to a change of the message's utility, thereby affecting the accumulated utility c_i. For example, when a vehicle moves from one geographical region to another or when a message becomes old.

The data selection process defines in a distributed manner the order in which messages are sent in the neighborhood and the vehicles to send these messages. Each vehicle calculates its local optimum solution based on the information received from one-hop neighbors, since acquiring global information is infeasible. This process is defined by Algorithm 1. U and $\vec{c}$ are the utility matrix and the vector of accumulated utility values for each vehicle, respectively. The core function is described in line 5. The Nash Bargaining solution maximizes the product of the sum of the utility gain u_{ij} and accumulated utility c_i of each vehicle. Therefore, in matrix U, message m_t maximizing $\prod_{i=1}^{h} [u_{ij} + c_i]$ will be selected. To guarantee that this product is higher when more neighbors are profiting, we set a lower bound $\varepsilon = 1$ for c_i. If a vehicle has m_t, then m_t is added to its queue of selected messages $\vec{q}$. However, to prevent transmission redundancies, each message selected should be sent by only one vehicle. Thus, in case there are multiple vehicles carrying m_t, the one farthest away from the previous sender of m_t will be selected, thereby allowing for a quick message dissemination. In each iteration, U is updated (lines 12 and 13) and the next optimum result is calculated. In the end, queue $\vec{q}$ defines which messages carried by each vehicle will be broadcast and at which order in the neighborhood.

Algorithm 1 FairDD_DataSelection

```
Input: $U$, $\vec{c}$ // matrix and vector of accumulated utility
Output: $\vec{q}$ // vehicle's queue of selected messages
 1: $q \leftarrow \oslash$
 2: $r \leftarrow 0$ // message's order to be sent in neighborhood
 3: $J \leftarrow \{0, 1, ..., n\}$
 4: while $U \neq \oslash$ do
 5:     $t \leftarrow \arg\max_{j \in J} \prod_{i=1}^{h} [u_{ij} + c_i]$
 6:     if vehicle has $m_t$ and is farthest from last sender then
 7:         $q.add(m_t, r)$ // add $m_t$ in $\vec{q}$, store its order $r$
 8:     end if
 9:     for each neighbor $i$ do
10:         $c_i \leftarrow c_i + u_{it}$
11:     end for
12:     remove $m_t$ from $U$
13:     remove $t$ from $J$
14:     $r \leftarrow r + 1$
15: end while
```

The complexity of Algorithm 1 is upper-bounded by the search of the maximum product in line 5. In total, $h \sum_{a=0}^{n} [n - a]$ operations are performed, where h and n are the number of vehicles and messages in the neighborhood, respectively. Since h is always limited by the transmission range, the complexity comes down to $O(n^2)$.

C. Protocol

We propose a network protocol that translates the message ordering defined by the data selection to the network. We consider periodic applications using broadcast communication, where the periodicity of an application is referred to as the application cycle. We define that vehicles are capable to synchronize their cycles to the Coordinated Universal Time (UTC), such as with a GPS device. This is in accordance to the IEEE WAVE standard [11] that defines that devices not capable of operating on multi-channels simultaneously must rely on such synchronization for vehicles to access the control channel (CCH) at specified time intervals.

The protocol is shown in Figure 1. In the beginning of each cycle, each vehicle calculates its queue of selected messages $\vec{q}$ with Algorithm 1. The application cycle is divided in equal time slots of size defined as the maximum time taken for each transmission. Each message is transmitted in the time slot number corresponding to the message's order r. If r exceeds the total number of time slots $n = (cycle/slottime)$, the message is scheduled to $[n-1]$. With this scheme, messages with higher priority are sent in earlier time slots compared with low priority messages. Since this order reflects the local optimum calculated by each vehicle individually, there is a chance that more than one message is sent in a single time slot. In this case, we introduce a small random delay before each transmission to prevent collisions. To keep the network load under a specified level, we define a suppression line that represents the total number of messages allowed to be sent in the neighborhood. Therefore, only messages scheduled after the suppression line are canceled.

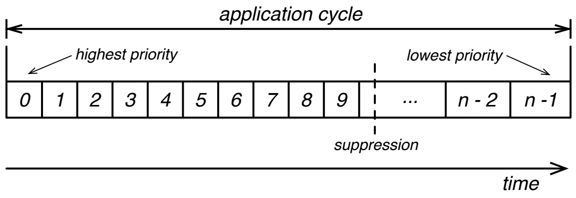


Figure 1. FairDD – synchronized suppression mechanism

As explained previously, the data selection mechanism depends on the current contextual knowledge acquired by each vehicle in order to build matrix U. For such purpose, we define periodic *hello messages* that are sent asynchronously in parallel with data messages. Each hello message sent by vehicle i contains a summarized list of messages carried by i with information such as message age and geographical region where it was generated. In addition, the following information is included: vehicle's ID, direction, final destination and accumulated utility c_i.

IV. PERFORMANCE EVALUATION

The performance evaluation of FairDD is carried out by means of simulations. Our goal is two-fold: (1) evaluate the advantages of employing data selection mechanisms to use the bandwidth more efficiently and (ii) compare FairDD's data selection with other approaches, namely:

1) *Altruistic*: based on the work presented in [6], this approach maximizes the total utility gain for all neighbors as a whole. Thus, it does not consider individual interest.
2) *No selection*: no utility is considered when selecting a data message. We simply define that messages with lower ID are sent first. Thus, messages with higher ID numbers are more likely to be suppressed.
3) *No suppression*: just as with *No selection*, no utility is used in the data selection. However, the maximum number of messages allowed by the application is sent. We define this maximum to be equal to the total number of neighbors.

We use OMNeT++ 4.1 simulator [12] with MiXiM v2.0.1. We adjust the implementation of IEEE 802.11b to comply with basic specifications of 802.11p. In the MAC layer, we set the bit rate to 3 Mbit/s, the Contention Window (CW) to values between 15 and 1023, the slot time to 13 μs, the SIFS to 32 μs, and the DIFS to 58 μs. In the physical layer, we operate in the 5.87 GHz frequency band, using 10 MHz of bandwidth. Based on estimates, we set the transmission power to 10 mW to achieve approximately 200 meters of interference range and 100 m of transmission range, assuming the Friis Free Space Path Loss (FSPL) propagation model with path loss coefficient equal to 3.5. The signal-to-noise threshold is set to 0.1259 mW, receiver sensitivity to -119.5dBm, and thermal noise to -110dBm.

Regarding the utility function, different results can be expected when different contextual information and parameters are considered by an application. Our goal is to define basic functions and parameters that can be common to various applications. Thus, the utility function u_{ij} is defined as:

$$u_{ij} = p(\alpha_1 z_1^i(m_j) + \alpha_2 z_2^i(m_j) + \alpha_3 z_3^i(m_j)). \qquad (3)$$

which is composed by the contextual knowledge functions:

Vehicle direction **(**α_1**,** $z_1^i(m_j)$**)**: if the vehicle i is going towards the data message's geographical region, z_1^i returns 1, otherwise it returns zero. α_1 is set to 0.3.

Closest distance to a message's region **(**α_2**,** $z_2^i(m_j)$**)**:

$$z_2^i(m_j) = 1 - d^i(c_{m_j})/5000 \qquad (4)$$

where $d^i(c_{m_j}))$ is a function which calculates the shortest distance in meters to which vehicle i approaches the message's geographical coordinates c_{mj}. α_2 is set to 0.6.

Data age **(**α_3**,** $z_3^i(m_j)$**)**:

$$z_3^i(m_j) = 0.999^{t_{mj}} \qquad (5)$$

where t_{mj} is the time elapsed since the message's generation time and α_3 is set to 0.1.

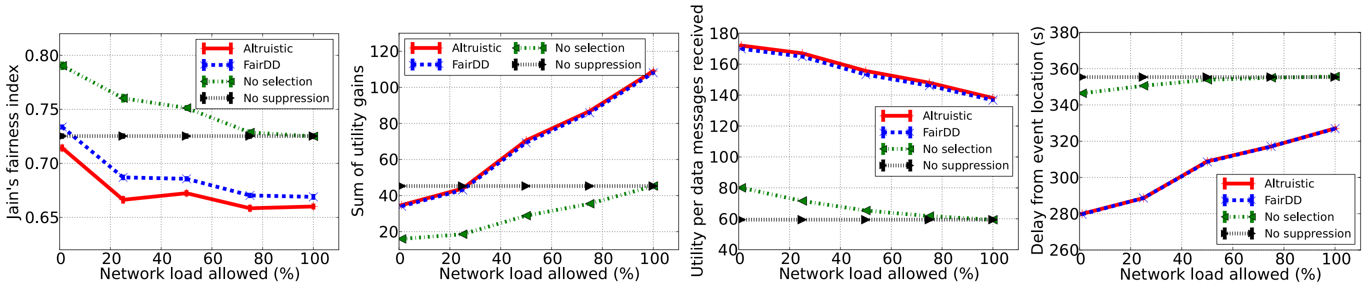
Data priority *(p)*: we define three levels of data priority for m_j: $p \in \{1.0, 0.5, 0.1\}$.

For all data selection mechanisms the protocol described in III-C is used. Both Hello messages and data messages are 2312 bytes large (the maximum allowed by 802.11p) and sent at 1 Hz. As explained, Hello messages are sent in in parallel without synchronization with the application cycle. Each slot time is set to 10 milliseconds, which is an overestimate of the transmission time with a bit rate of 3 Mbit/s.

Every vehicle begins the simulation with 10 data messages. Each message's geographical coordinates are set to the Cartesian point corresponding to 500 meters away from the vehicle in the opposite vehicle's direction. In this manner, we simulate vehicles that have already passed by the message's geographical region and now carry the message to other regions. The start age of messages is defined as a random number in $[0, 300]$ seconds. The three levels of data priority are assigned for each message according to lane ID number ln at which the vehicle begin in the simulation by: $ln \bmod 3$.

Our evaluation considers the following metrics:

- ***Jain's fairness index***: defined as $(\sum_i^h x_i)^2/(h\sum_i^h x_i^2)$ (see [13]), where h is the total number of vehicles and x_i is the sum of utility gained by vehicle i. It indicates how well utility gains are distributed among vehicles. $1/h$ and 1 are the worst and best cases, respectively.



(a) Jain's fairness x network load (b) Utility gains x network load (c) Utility/receptions x network load (d) Average delay x network load

Figure 2. Results with 95% confidence intervals for increasing network load levels allowed by FairDD's suppression mechanism

- ***Sum of utility gains***: the total utility sum gained by an arbitrary vehicle on average. It measures the overall performance of the dissemination approach.
- ***Utility per data messages received***: shows the bandwidth utilization efficiency of the approach in terms of how much utility is gained per each data message received on average.
- ***Delay***: the average amount of time taken from the message's generation until it is received by vehicles that will be traveling to the area (1 km^2) to which the message relates.

In the next sections, we describe the results for a urban scenario with increasing network load levels (Section IV-A) and a highway scenario with increasing network densities (Section IV-B). Both scenarios were created with SUMO [14]. Therefore, they include realistic mobility patterns such as vehicle overtaking, lane changing, and rely on the well-known Krauß car-following mobility model.

A. Urban scenario with increasing controlled network load

In this section, we compare FairDD with approaches 1–3 when increasing network load levels are allowed by the suppression mechanism presented in Section III-C. The network load is defined as the percentage of neighbors that are allowed to send a data message, varying from 1 to 100%. Therefore, suppression is applied whenever the combined number of messages transmitted and received by a vehicle exceeds such defined percentage. In this case, the results for the approach with no suppression are fixed to 100%.

We consider a sparse urban scenario by taking a map fragment of the city of Enschede, The Netherlands. This segment has an area of 3.5 x 4 km^2 and was retrieved with OpenStreetMaps [15]. The number of vehicles simultaneously moving increases linearly with time from 0 to 200, with a total of 300 generated. Vehicles' speeds vary from 0 to 100 km/h. Simulations consist of 20 runs of 300 seconds and with vehicles moving at intervals of 1 second.

Figure 2(a) shows the results of applying the Jain's fairness index. Since it is broadcast communication, as network loads increase more messages are sent and even vehicles with high accumulated utilities may still increase their utilities. Thus, the level of fairness tends to decrease. For all network load levels allowed, FairDD presents a higher fairness index compared with Altruistic. However, employing no selection shows a even higher value compared with FairDD. In fact, this is simply a result of the criteria used in this approach for the ordering of messages: messages with lower ID are always selected first and thus similar utility values are distributed.

Although with a higher fairness index, approaches with no data selection present lower values of the sum of utility gains as shown in Figure 2(b). In fact, even restricting the number of messages transmitted both FairDD and Altruistic achieved higher values of utility gain when compared with the approach with no suppression. FairDD and Altruistic present almost identical results. Generally, when higher loads are allowed more messages are sent and, thus, more utility is gained on average per vehicle.

When looking at the utility per data messages received (Figure 2(c)), there is a clear advantage when using data selection mechanisms. Such ratio is more than the double compared with approaches with no data selection. With higher network load levels allowed, this ratio decreases as messages with less priorities are selected later on.

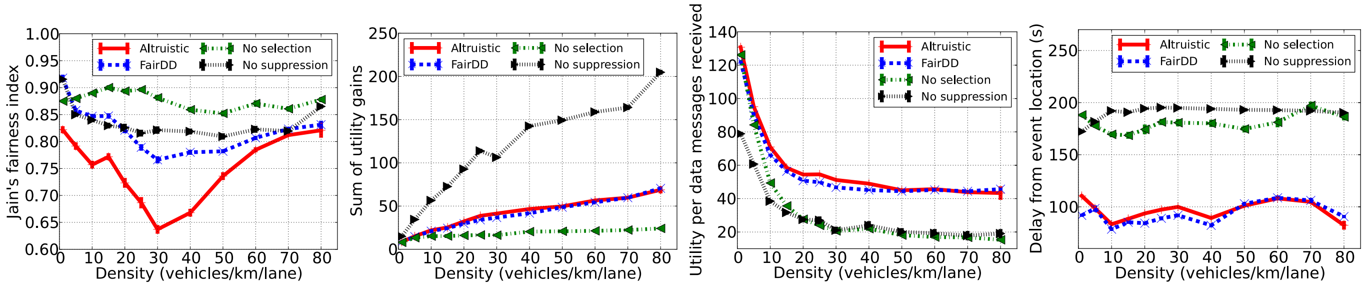
Finally, in Figure 2(d) the results for the average delay are presented. Applying data selection shows again a clear gain in performance compared to no use of selection. Since the utility is calculated based on the direction and final destination of vehicles, maximizing the utility gain of vehicles leads to a more quickly distribution of relevant data to those "interested" vehicles actually traveling towards the geographical region of the messages.

These results show the advantages of employing data selection: the network is utilized more efficiently in terms of utility gain per message received and relevant data is more quickly spread to interested vehicles. Also, FairDD presents a higher fairness index compared with Altruistic and yet maintaining equivalent results in the remaining parameters.

B. Highway scenario with increasing network densities

We consider a highway scenario with densities varying from 1 to 80 vehicles/km/lane. For all approaches employing data selection the maximum network load is set to the minimum. Therefore, only data messages assigned to the earliest time slot (highest priority) are allowed to be sent.

The road is a 1-kilometer straight highway with two lanes in each road direction. Vehicles' speeds vary according to the density considered by following the Krauß mobility model, i.e., the higher the density is, the slower vehicles move. Simulations consist of 20 runs of 100 seconds and with vehicles moving at intervals of 1 second.



(a) Jain's fairness x density (b) Utility gains x density (c) Utility/receptions x density (d) Average delay x density

Figure 3. Results with 95% confidence intervals for increasing network densities

Figures 3(a) and 3(b) show the results of applying the Jain's fairness index and the sum of utility gains for various densities. When higher densities are considered, more messages are transmitted due to the higher number of vehicles. Thus, the sum of utility gain per vehicle tends to increase. Also, in higher densities vehicles move more slowly, which gives more time for a complete data exchange among adjacent vehicles. For this reason, the index of fairness becomes higher and similar for all approaches. Notably, FairDD presents up to 20% higher index of fairness compared to Altruistic. Although the approach with no data selection presents higher values of fairness compared to approaches employing data selection, its values in terms of the sum of utility gains (efficiency) are considerably lower.

When no suppression is applied, the number of messages inserted into the network increases almost at the same rate as the density increases. Thus, the sum of utility gain is higher than all other approaches. However, as shown in Figure 3(c), the utility per message ratio of such approach is 50% lower than approaches with data selection. Results for all approaches also show a decrease in the ratio up to an almost constant level as density increases. In fact, with more vehicles moving at slow speeds, the same group of vehicles tends to remain together. Thus, it is more likely that after some time messages with lower utility values are exchanged.

Finally, as observed in the previous section, employing data selection mechanisms brings the average delay down to almost 50% compared with approaches with no data selection (Figure 3(d)). In this scenario, such delay values remained around a constant upper-bound for all densities.

Overall, the advantages of employing data selection mechanisms remain valid for various network densities. More importantly, FairDD shows a gain up to 20% in fairness compared with Altruistic and yet it presents equivalent results in sum of utility gains, utility per message ratio and delay.

V. CONCLUSION AND FUTURE WORK

This paper has presented FairDD, a periodic dissemination protocol that achieves a fair distribution of application data utility throughout the network while keeping the network load under a defined level. With simulation, we have shown that: (i) by employing data selection the network is utilized more efficiently in terms of utility gain per data message received and relevant data is more quickly spread to interested vehicles; and more importantly (ii) FairDD presents a higher fairness index compared with other approaches and yet it maintains a high level of bandwidth utilization efficiency.

In future work, we will focus on making FairDD suitable to adaptive application cycles and network loads. Also, we plan to evaluate the necessary frequency of messages carrying context information used in the data selection process.

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