Fair and Adaptive Data Dissemination for Traffic Information Systems

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***Abstract*—Vehicular Ad-hoc Networks (VANETs) are expected to serve as support to the development of not only safety applications but also information-rich applications that disseminate relevant data to vehicles. Due to the continuous collection, processing, and dissemination of data, one crucial requirement is the efficient use of the available bandwidth. Firstly, the rate of message transmissions must be properly controlled in order to limit the amount of data inserted into the network. Secondly, messages must be carefully selected to maximize the *utility* (benefit) gain of vehicles in the neighborhood. We argue that such selection must aim at a *fair* distribution of data utility, given the possible conflicting data interests among vehicles.**

In this work, we propose a data dissemination protocol for VANETs that distributes data utility fairly over vehicles while adaptively controlling the network load. The protocol relies only on local knowledge to achieve fairness with concepts of Nash Bargaining from game theory. Simulation results show that our algorithm presents a higher fairness index and yet it maintains a high level of bandwidth utilization efficiency compared to other approaches. In addition, the rate of transmissions is adaptively controlled as new information about the environment is collected.

Keywords: Vehicular Ad-hoc Networks (VANETs), Traffic Information Systems, Data Dissemination, Data Utility, Fairness

I. Introduction

With Vehicular Ad-hoc Networks (VANETs), numerous applications are expected to aid drivers not only with safety-related information but also with general traffic data such as the current traffic condition and parking information. In particular, Traffic Information Systems (TIS) form an important category of non-safety applications that aim to enhance passenger comfort and traffic efficiency [1]. The information produced by these systems is generally more frequent but also valid for a longer period of time compared to emergency data. This characteristic poses specific requirements and challenges for the design of data dissemination protocols.

Due to the continuous collection, processing, and dissemination of data, one crucial requirement in TIS is the *efficient* use of the available bandwidth. The amount of data collected can increase quickly even with aggregation algorithms. In addition, the time window for data exchange can be very limited due to the rapidly changing road environment. Firstly, the rate of message transmissions must be properly controlled in order to limit the amount of data inserted into the network. Secondly, as a consequence, messages must be carefully selected by means of data selection mechanisms in order to maximize the *utility* (benefit) gain of vehicles in the neighborhood. We argue that such mechanisms must aim at a *fair* distribution of data utility, given the possible conflicting data interests among vehicles. As exemplified in Figure 1, vehicles moving in opposite directions are potentially interested in each other's data, since a group of vehicles in one direction holds data related to the destination of vehicles in the opposite direction. If we consider a hypothetical situation where there is only time/bandwidth for the exchange of two messages, a fair approach would choose messages m_1 and m_4, thereby providing a gain of 0.9 of utility to vehicles moving to Enschede and a gain of 0.7 to vehicles moving to Hengelo. In contrast, an altruistic-based approach [2] that maximizes the total utility gained by all vehicles in the neighborhood would choose m_1 and m_2, thereby leaving vehicles in one direction with no information about their destination.

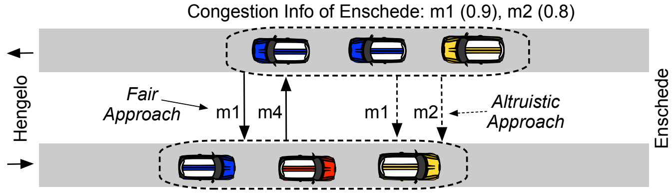


Figure 1. Motivation for a *fair* data selection. A fair approach leads to a more even distribution of utility, providing traffic awareness to vehicles in both road directions.

In this work, we address both problems of controlling the network load and selecting data in a road environment where vehicles have conflict of data interests. Our contribution lies in presenting a broadcast-based data dissemination protocol that distributes data utility fairly over vehicles while adaptively controlling the network load, which we refer to as FairAD: *Fair* and *A*daptive data *D*issemination. The protocol relies only on local knowledge to achieve fairness with concepts of Nash Bargaining from game theory. FairAD is a result of combining two independent lines of work, namely, the data selection mechanisms discussed in [3], [4] and the adaptive beaconing control proposed in [5], [6].

The remainder of this paper is organized as follows. In Section II, we outline relevant related works and motivate the contribution of this work. Section III details the functioning of FairAD. The validation of FairAD is presented in Section IV. Finally, Section V concludes this paper.

II. Related Work

One of the earliest works proposing the use of application utility for data selection is [2]. Authors focus on solving scalability issues in disseminating data in VANETs by selecting messages that maximize the total utility gained by all vehicles in the neighborhood. Differently, authors in [7] introduce a protocol that allows content to remain available in areas where vehicles are most interested in it. A detailed study of using utility to reduce the uncertainty of sensor data gathered by vehicles is presented in [8]. Similar to this work is [9], where authors consider the average system information age to maintain up-to-date state information among all nearby vehicles. Finally, [10] presents an information dissemination function to maximize the total utility across all applications while respecting communication constraints.

One key aspect missing in these works is the consideration of utility fairness when vehicles have conflicting interests. Although in [11] 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 [12]. However, the data selection considered is restricted to only pairs of vehicles. In [3], we go one step further and present a generalized and fully distributed approach for utility data selection suitable for broadcasting communication.

With respect to controlling the load in the radio channel, numerous works have focused on either adjusting the power level or transmission rate of messages [13]–[15]. However, such works focus mainly on disseminating safety beacons that are valid for a very short period of time to provide cooperative awareness. In this work, we are rather interested in approaches that control the network load when messages carrying application data have to be disseminated throughout the network, for longer distances and timespans.

In this line, the protocol presented in [16] determines the data rate of each vehicle based on the application utility of each message in the transmission queue. Similarly, [17] proposes a method for controlling the network congestion by considering different aspects such as the message priority and vehicles' speeds. Different forms of data aggregation have also been used to improve the quality of information exchanged and reduce the network load inserted into the network. Among works following this approach is the Self-Organizing Traffic Information System (SOTIS) [18]. It stores information in the form of annotated maps of different resolutions and performs information exchange through a specialized MAC protocol. Instead of relying on a ad-hoc network, the PeerTIS [19] builds a peer-to-peer overlay over the Internet by means of cellular network to provide data about the current road traffic conditions.

One major drawback of these solutions is that they either focus on message utility or network load control in order to address scalability issues of data dissemination in VANETs. To the best of our knowledge, the Adaptive Traffic Beaconing (ATB) [5], [6] pioneered an approach that combines both aspects into one adaptive transmission rate control. However, just as with other approaches that define the message utility, it lacks the consideration of utility fairness when vehicles have conflicting interests. In this work, we extend and improve ATB by combining it with concepts introduced in our previous work in [3] to achieve data utility fairness in the neighborhood.

III. Fair and Adaptive Data Dissemination

FairAD aims to achieve a *fair* distribution of data utility throughout the network while controlling the network load. It consists of two main components: (i) a distributed fair data selection mechanism based on FairDD [3] and (ii) an adaptive periodic protocol based on ATB [5], [6] to control the rate at which messages are broadcast into the network.

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 v_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. FairAD relies on the Nash Bargaining [20] 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. In [20] it is proved that in a convex, closed and bounded set the solution is unique for the axioms: Pareto optimality, symmetry, scale covariance, and independence of irrelevant alternatives.

A vehicle v_i employing FairAD independently stores its *local* knowledge of the neighborhood into two variables: utility matrix U and vector of accumulated utility c_i.

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

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

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 v_i already has message j, then $u_{ij} = 0$.

One main feature of FairAD is that we take into account the accumulated utility c_i of each vehicle v_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 gain non-zero utility from overhearing. Another property of c_i is that it continually changes depending on the current context of v_i. A change of context might lead to a change of the message's utility (see Equation (1)), thereby affecting c_i. For example, when a vehicle moves from one geographical region to another or when a message becomes old. Figure 2 shows the evolution of c_i when a random vehicle i moves in one of our simulation scenarios. The utility function considered takes into account the vehicle direction, closest distance to message's region, message age, and message priority (detailed in Section IV). A vehicles starts receiving utility but as time goes by or as the vehicles changes its direction, its accumulated utility c_i begins to fluctuate.

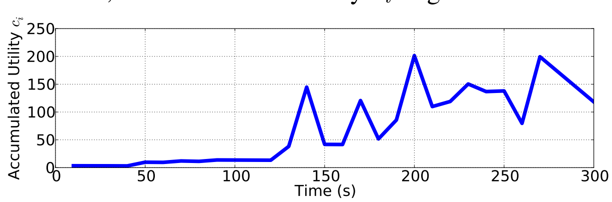


Figure 2. Example of the accumulated utility (c_i) concept for a random vehicle moving in the city of Enschede, The Netherlands.

The data selection process defines in a distributed manner the next message each vehicles sends and its priority in terms of fairness, given the accumulated utility and messages carried by neighbors in the neighborhood. Each vehicle calculates its optimum solution locally, based on the information received from one-hop neighbors only. This process is defined by Algorithm 1. The input values U and $\vec{c}$ are the utility matrix and a vector containing the accumulated utility values c_i of each vehicle, respectively. The algorithm gives as output the message selected m_t having the highest priority P among the messages carried by the local vehicle, where lower values of P indicate higher priority.

The core function is described in line 4. 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. Each vehicle stops its search when it has the m_t of the current loop iteration r, where r represents the rank of the message with respect to other messages in the neighborhood. However, to prevent transmission redundancies when multiple vehicles have m_t, a small extra value $S_v\delta$ is considered for the final priority P (line 8), where δ is a constant value (e.g., 0.1) and S_v is the order of the local vehicle in the list of one-hop neighbors sorted by their distance to the location where m_t was generated. The goal is to give higher chance for vehicles farther away from the message's event location to broadcast the message first, thereby allowing for a quick data dissemination. Other vehicles carrying m_t but with lower priority could then cancel and reselect their messages.

Algorithm 1 FairAD_DataSelection

Input: U, $\vec{c}$ // *matrix and vector of accumulated utility*
1: $r \leftarrow 0$ // *counter to define the final message rank*
2: $J \leftarrow \{0, 1, ..., n\}$
3: **while** $U \neq \oslash$ **and** $r < r_{max}$ **do**
4: $\quad t \leftarrow \arg\max_{j \in J} \prod_{i=1}^{h} [u_{ij} + c_i]$
5: $\quad$ **if** this vehicle has m_t **then**
6: $\quad\quad$ **if** number of neighbors with $m_t > 0$ **then**
7: $\quad\quad\quad$ **sort** vehicles by distance from event location
8: $\quad\quad\quad$ $r \leftarrow r + (S_v\delta)$ // *S_v is the order of this vehicle*
9: $\quad\quad$ **end if**
10: $\quad\quad$ $P \leftarrow \left(\dfrac{r}{r_{max}}\right)$
11: $\quad\quad$ **return** m_t, P // *message selected and its priority*
12: $\quad$ **end if**
13: $\quad$ remove m_t from U
14: $\quad$ remove t from J
15: $\quad$ $r \leftarrow r + 1$
16: **end while** // *no message selected, try again later*

Whenever a message is not selected, U is updated (lines 13–14) and the next optimum result is calculated in the following iteration. The final value of P lying in the interval $[0, 1]$ is defined in line 10. The maximum message rank r_{max} serves to limit the number of messages considered in each data selection in order to: (i) control how spread messages are in the interval $[0, 1]$; and (ii) prevent long processing time when a large number of messages is available in the neighborhood. Reaching r_{max} and not selecting a message is an indication that this vehicles has messages with lower priority compared to its neighbors and can try later. The vehicle runs the algorithm again as soon as new information about the environment is received, as we describe in the following sections.

The complexity of Algorithm 1 is upper-bounded by the search of the maximum product in line 4. In the worst case, i.e., when $r_{max} = n$, 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. As the number of vehicles h is always limited by the transmission range employed by neighbors, the complexity comes down to $O(n^2)$.

C. Adaptive Message Intervals

We propose the use of Adaptive Traffic Beacon (ATB) [5], [6] as our means to control the rate at which messages are transmitted in the network. ATB is designed to ensure a congestion-free channel by preventing packet loss (collisions) while reducing the messages's end-to-end delay. To achieve its goal, ATB adaptively controls the *interval* between transmissions of a given vehicle by relying on two metrics: (i) the *channel quality* C and (ii) the *message priority* P.

The message priority P determines the importance of each message in the current network context, i.e., in the current set of neighbors. It allows messages with higher priority to be transmitted first. In ATB's implementation in [5], [6], P combines and weighs specific metrics, namely, the data age, distance to event source, distance to the next Road-Side Unit (RSU), and how well the information has already been disseminated. However, different applications may require different metrics to be considered. In addition, one aspect missing in this calculation is the different interests that vehicles might have in a certain message. To this end, we improve the calculation of P by considering our generalized *utility* function as described in Section III-A. In this manner, we provide a flexible framework for applications to define which aspects to consider according to their specific needs. More importantly, we use our algorithm described in Section III-B to provide a fair distribution of utility among neighbors without compromising efficiency in terms of the total utility distributed. Therefore, P is the priority of the message selected by Algorithm 1 according to the Nash Bargaining principle.

The channel quality C combines three different network metrics in order to estimate the availability of channel resources as detailed in [5], [6]:

i) Number of collisions or bit errors K observed in the last time interval. It gives an estimate of the recent load on the channel:

$$K = 1 - \left(\frac{1}{1 + \text{\# collisions}} \right). \tag{3}$$

ii) The current Signal to Noise Ratio (SNR) as perceived in the last transmission estimates the current transmission quality. It is denoted as S:

$$S = \max \left\{ 0; \left(\frac{\text{SNR}}{\text{max. SNR}} \right)^2 \right\}. \tag{4}$$

iii) Finally, number of neighbors N, i.e., neighborhood density, is used to predict the probability of other transmissions in the next time interval:

$$N = \min \left\{ \left(\frac{\text{\# neighbors}}{\text{max. \# neighbors}} \right)^2 ; 1 \right\}. \tag{5}$$

In order to give higher weight to metrics K and S, factor $w_C \geq 1$ is used to combine the three components as follows:

$$C = \frac{N + \left[\omega_C \left(\frac{S+K}{2} \right) \right]}{1 + \omega_C}. \tag{6}$$

The combination of both parameters C and P is given by (7). Smaller values of C and P represent a better channel and a higher priority, respectively. Therefore, when both values are zero $I = I_{min}$, i.e., the shortest interval allowed, where $I \in [I_{min}, I_{max}]$. The weight of each parameter is determined by factor w_I. The quadratic form in both parameters C and P is used to quickly reduce I when the channel quality improves and/or when the message priority increases.

$$I = I_{min} + \left[(I_{max} - I_{min})(\omega_I C^2 + (1 - \omega_I) P^2) \right]. \tag{7}$$

D. Adaptive Periodic Protocol

We propose an adaptive protocol that continually reevaluates the next data message to be sent and its priority, whenever new information about the environment is received. Two types of messages are defined: *hello* messages and *data* messages.

As explained previously, the data selection mechanism proposed in Section III-B depends on the current contextual knowledge acquired by each vehicle to build matrix U. For this purpose, we define auxiliary *hello* messages that are broadcast continually by each vehicle. Each hello message sent by vehicle v_i contains a summarized list of data messages carried by v_i with information such as age and the geographical region where each message was generated. In addition, these messages include up-to-date information about the vehicle such as the vehicle's ID, direction, final destination and accumulated utility c_i. The information about the vehicle is always included in the header of each hello message. However, to guarantee an upper-bound for the processing time of Algorithm 1, the list size is kept under the maximum message size allowed by the underlying protocol, i.e., 802.11p. In such cases, vehicles are required to include in the list messages that are expected to be most important to other vehicles according to the data selection scheme. This is done by executing Algorithm 1 with only the files carried by vehicle v_i, i.e., subset U_i, multiple times without repeating the files chosen in each iteration until the maximum list size is reached.

On the other hand, *data* messages carry the actual data distributed by the application. In contrast to hello messages, data messages are only scheduled when at least one neighbor can benefit from it, i.e., utility > 0. Therefore, if all neighbors already shared their messages and no new message is generated, then no more data messages are transmitted.

As defined in [21], vehicles shall be able to accommodate an architecture that supports a control channel (CCH) and multiple service channels (SCHs). Therefore, we define each type of message to be sent in a separate radio channel in order for hello messages not to interfere with the transmission of data messages. The transmission interval for both message types is defined according to (7), where I_h and I_d are the intervals defined for hello and data messages, respectively. In particular, we define $w_I = 1$ for I_h. As hello messages are equally important, $w_I = 1$ guarantees that only the channel quality C is taken into account.

The complete protocol diagram is shown in Figure 3. The upper part of the diagram shows the process of scheduling

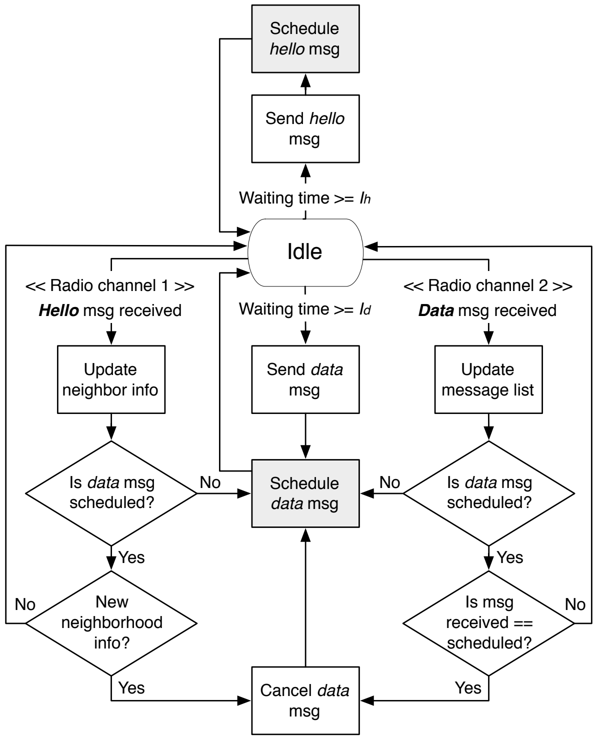


Figure 3. FairAD protocol diagram

Table I
SIMULATION PARAMETERS

Physical Layer	Frequency band	5.88, 5.89 GHz
	Bandwidth	10 MHz
	Transmission range	~100 m
	Tx power α	10 mW
	FSPL exponent α	2.2
	Receiver sensitivity	-85 dBm
	Thermal noise	-110 dBm
	Bit Error Rate (BER)	Based on [24]
Link Layer	Bit rate	18 Mbit/s
	CW	[15,1023]
	Slot Time	13 μs
	SIFS	32 μs
	DIFS	58 μs
FairAD	r_{max}	5
	δ	0.1
	max. SNR (S)	50 dB
	max. # neighbors (N)	50
	w_C	2
	I_{min} (hello msg)	1 s
	I_{max} (hello msg)	5 s
	w_I (hello msg)	1
	I_{min} (data msg)	30 ms
	I_{max} (data msg)	60 s
	w_I (data msg)	0.5
Scenarios	Data message size	2312 bytes
	Initial # messages	5
	Max. msg list size in hello	100
	# runs	30

and sending hello messages. Whenever I_h expires, a hello message is sent and a new one is scheduled. The lower part shows the decision tree for scheduling data messages. A new data message is immediately scheduled if no data message is already scheduled and a new hello message or data message is received from other neighbors. Every data message selection in the function *Schedule data msg* is done by Algorithm 1. The protocol also takes care of canceling previously scheduled messages if new relevant information is received in hello messages or if another neighbor farther away from the message's event location has already disseminated the data message scheduled. In this way, we guarantee an optimum message selection according to the most up-to-date contextual information. After canceling and scheduling a new data, the new interval defined refers always to the last time a message was sent, thereby respecting the condition $I \in [I_{min}, I_{max}]$.

IV. PERFORMANCE EVALUATION

The performance evaluation of FairAD is carried out by means of simulations. Our goal is two-fold: (i) verify the benefits of employing data selection mechanisms in the adaptive periodic data dissemination protocol described in Section III-D and (ii) compare FairAD's data selection with other data selection approaches, namely:

1) *Altruistic*: based on [2], it maximizes the total utility gain for all neighbors as a whole. Thus, it does not consider individual interest. It gives an upper-bound in terms of efficiency for individual message selections.
2) *Max-min*: maximizes the utility of vehicles with the lowest accumulated utility. It is an alternative to Nash Bargaining with respect to achieving fairness [22]. It gives an upper-bound in terms of fairness for individual message selections.
3) *No selection*: no utility is considered when selecting a data message. We simply define that messages with lower ID are sent with higher priority.

We use the Veins[1] framework [23] version 2.0-rc2, which is based on both OMNeT++ 4.2.2[2] event-driven network simulator and SUMO[3] for road traffic microsimulation. Veins provides realistic models for the 802.11p DSRC PHY and MAC layers, including multi channel operation required by our adaptive protocol in FairAD. At the same time, SUMO allows the creation of scenarios that include realistic mobility patterns such as vehicle overtaking, lane changing, and rely on the well-known Krauß car-following mobility model.

The complete list of simulation parameters is shown in Table I. The parameters for the PHY and MAC layers are defined in such a way that complies with the 802.11p standard. We use channels 5.88 and 5.89 GHz for data and hello messages, respectively. In FairAD, we choose $r_{max} = 5$ to provide a large separation in time between messages selected by different vehicles in the interval $[I_{min}, I_{max}]$ and $\delta = 0.1$ to let vehicles farther away from the message's event location broadcast first. Since hello and data messages are used for different purposes, we set a different interval $[I_{min}, I_{max}]$ for each type. On the one hand, hello messages should be always broadcast to provide neighborhood awareness. Therefore, we

[1] veins.car2x.org [2] www.omnetpp.org [3] sumo.sourceforge.net

limit the range to $[1, 5]$. On the other hand, the interval for data messages should be large enough to allow for a separation in time between messages of different priorities. Hence, we set this interval to $[0.03, 60]$, as proposed in [5], [6]. We also set a different value to w_I for each message type, namely, $w_I = 1$ and $w_I = 0.5$ for hello and data messages, respectively. $w_I = 0.5$ assigns equal importance to both channel quality C and message priority P. Giving a higher weight to P is particularly useful for the evaluation of different data selection mechanisms, since differences in priority will be quickly reflected in the interval assigned.

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. The utility function u_{ij} is defined as the product:

$$u_{ij} = \beta \left(\alpha_1 z_1^i(m_j)\right) \left(\alpha_2 z_2^i(m_j)\right) \left(\alpha_3 z_3^i(m_j)\right). \quad (8)$$

which is composed by the contextual knowledge functions:

***Vehicle direction* (α_1, $z_1^i(m_j)$)**: if the vehicle v_i is going towards the data message's geographical region, z_1^i returns 1, otherwise it returns 0.1. α_1 is set to 3.

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

$$z_2^i(m_j) = 1 - \frac{d^i(c_{m_j})}{\sqrt{x_{max}^2 + y_{max}^2}} \quad (9)$$

where $d^i(c_{m_j})$ is a function which calculates the shortest distance in meters to which vehicle v_i approaches the message's geographical coordinates c_{mj} and x_{max}, y_{max} are the maximum x and y cartesian values of the scenario being considered. α_2 is set to 6.

***Data age* (α_3, $z_3^i(m_j)$)**:

$$z_3^i(m_j) = 0.999^{t_{mj}} \quad (10)$$

where t_{mj} is the time elapsed since the message's generation time and α_3 is set to 1.

***Data priority* (β)**: we define three levels of data priority for m_j: $\beta \in \{1.0, 0.5, 0.1\}$. Note that this is a fixed value defined by the application and different from the message priority P defined in Algorithm 1.

Every vehicle begins the simulation with 5 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***: calculated each time a vehicle selects and sends a data message; defined as $(\sum_i^h c_i)^2/(h \sum_i^h c_i^2)$ (see [25]), where h is the number of vehicles in the neighborhood and c_i is the accumulated utility of each neighbor v_i after receiving the message selected. It indicates how well data utility is distributed among vehicles. $1/h$ and 1 are the worst and best cases, respectively.
- ***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.
- ***Total number of transmissions***: the total number of *data* messages transmitted on average by an arbitrary vehicle. It indicates how well the adaptive periodic protocol copes with changes in the network load.
- ***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 to which the message relates. The area radius is defined as: $\frac{1}{4}\sqrt{x_{max}^2 + y_{max}^2}$, where x_{max} and y_{max} are the maximum x and y cartesian values of the scenario being considered.

In the next sections, we show the applicability of FairAD in both an urban scenario with increasing data message list sizes (Section IV-A) and a highway scenario with increasing network densities (Section IV-B).

A. Urban scenario with increasing data message list sizes

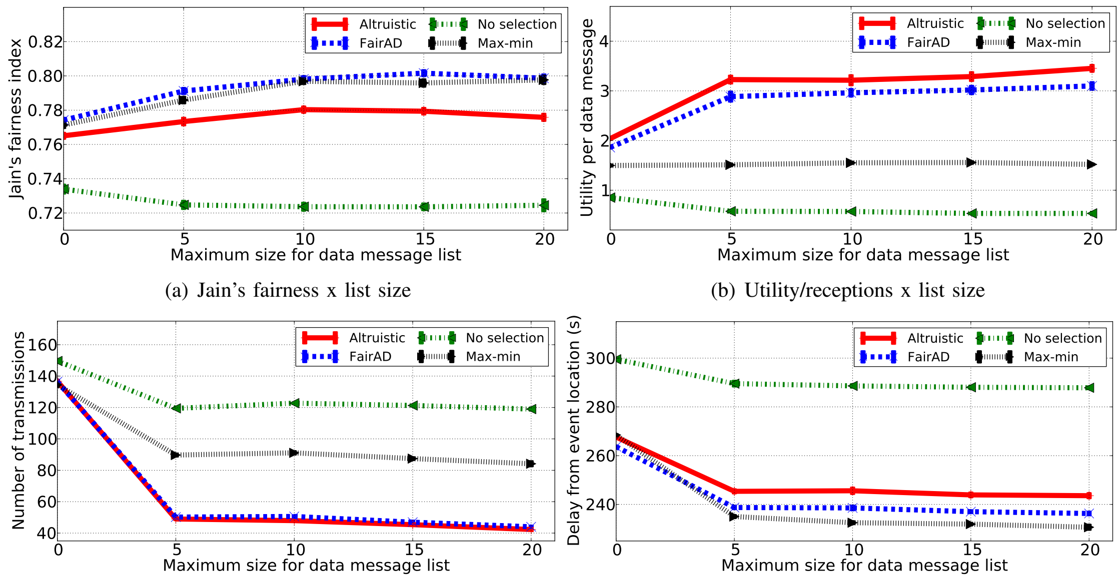
In this section, we compare FairAD with approaches 1–3 when increasing the maximum size allowed for the message list that is included in hello messages. In this way, we evaluate the impact of how much awareness is necessary for vehicles to efficiently select and distribute data in the neighborhood. We vary the maximum number of messages from 0 to 20, where zero means that vehicles are limited to select messages based only on its local list. In this scenario, vehicles receive on average from 30 to 40 messages in the simulation time.

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[4]. 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 30 runs of 300 seconds.

Figure 4(a) shows the results of applying the Jain's fairness index. Specially for FairAD and Max-min, the level of fairness increases as more information about the messages available in the neighborhood is known. As these approaches focus on fairness, more contextual information enables a more precise data selection that will please individual interests of vehicles.

With more messages in the list, vehicles are also able to transmit fewer messages and more efficiently as shown in Figures 4(b) and 4(c). Notably, Altruistic and FairAD are able to increase efficiency and choose messages with highest utility to be distributed, thereby outperforming Max-min and No selection in terms of the utility per message ratio. In contrast, Max-min aims only to increase the utility gain of vehicles with lowest accumulated utility, which compromises the efficiency in terms of the total utility distributed.

[4] www.openstreetmap.org



(a) Jain's fairness x list size

(b) Utility/receptions x list size

(c) Number of transmissions x list size

(d) Average delay x list size

Figure 4. Results with 95% confidence intervals for increasing sizes of the data message list included in hello messages

Finally, Figure 4(d) shows the results for the average delay. All approaches benefit from increasing the message list size, as vehicles can keep track of messages that have already been received by other vehicles and avoid duplicate broadcasts. However, applying data selection leads to lower delay values compared to No selection. Since the direction and final destination of vehicles are considered in the utility calculation, mechanisms considering utility in the data selection are able to distribute messages more quickly to "interested" vehicles that are actually traveling towards the message's event region.

Overall, increasing the message list size allows for data selection methods to better achieve their specific goals of efficiency (Altruistic), fairness (Max-min), and both (FairAD). This is true even for small list sizes, thanks to the policy adopted to include messages that are predicted to be most beneficial to other neighbors. Notably, FairAD achieves the best compromise between fairness and efficiency.

B. Highway scenario with increasing network densities

We consider a highway scenario with densities varying from 5 to 100 vehicles/km/lane. Simulations consist of 30 runs of 100 seconds. The road is a 1-kilometer straight highway with two lanes in each road direction. The speed of vehicles reaches a maximum of 120 km/h in very sparse scenarios. When increasing the density, the speed varies according to the Krauß mobility model, i.e., the higher the density is, the slower vehicles move. Note that the space between vehicles varies, with small traffic jams occurring in each road end. Thus, the number of data exchanges and, consequently, results do not present a perfect linear behavior with increasing densities.

Figure 5(a) shows the results of applying the Jain's fairness index for various densities. FairAD and Max-min show up to 15% and 25% higher fairness index compared to Altruistic, respectively. No selection shows a higher value compared to FairAD, which is simply a result of the criteria used by No selection to assign messages' priority: messages with lower ID are selected first and thus similar utility values are distributed.

As the density increases, the adaptive protocol based on ATB properly controls the network load by increasing the time interval between transmissions with higher values of C in Equation (7). This results in a lower number of transmissions for all methods (Figure 5(c)). The number of transmissions varies between data selection methods due to their differences in selecting the message priority P of the same equation. With fewer messages transmitted, methods that aim at efficiency such as Altruistic and FairAD show an improvement in the utility per message ratio and outperform Max-min and No selection, as shown in Figure 5(b). However, this comes at the cost of decreasing their performance in terms of fairness.

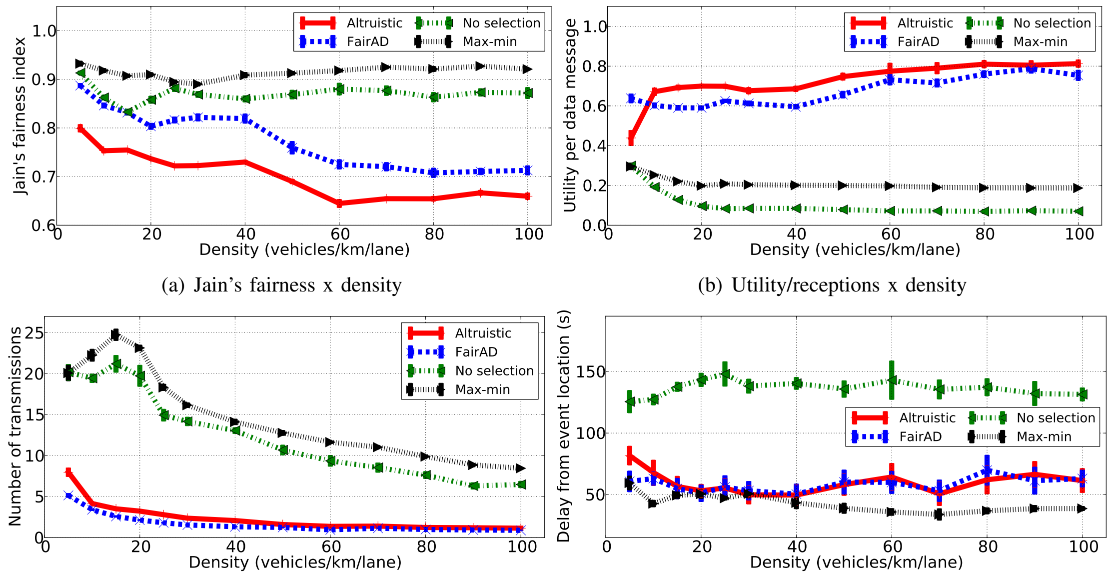
Finally, as pointed out previously, employing data selection mechanisms clearly helps decrease the average delay compared with No selection, as shown in Figure 5(d).

These results show that FairAD is able to adaptively distribute data utility fairly over vehicles and properly control the network load for increasing network densities.

V. Conclusion and Future Work

This paper has presented FairAD, a dissemination protocol that utilizes the available bandwidth efficiently by maximizing the data utility gain of vehicles in the neighborhood and controlling the network load inserted into the network. It combines both a data selection algorithm to distribute application data utility fairly over vehicles and an adaptive transmission rate control to limit the number of messages broadcast.

Simulation results verify the benefits of employing data selection mechanisms in terms of efficiency and delay in delivering relevant data to interested vehicles. In comparison with other approaches, FairAD presents a higher fairness index and yet it maintains a high level of bandwidth utilization efficiency. In every scenario considered, the protocol shows to



(a) Jain's fairness x density

(b) Utility/receptions x density

(c) Number of transmissions x density

(d) Average delay x density

Figure 5. Results with 95% confidence intervals for increasing network densities

adaptively control the rate of transmissions as new information about the environment is collected.

In future work, we will focus on designing and testing utility functions for different applications' requirements.

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