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# On the applicability of fair and adaptive data dissemination in 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. We show the applicability of the protocol by giving example of utility functions for two Traffic Information Systems (TIS) applications: (i) parking-related and (ii) traffic information applications. The protocol is validated with both real-world experiments and simulations of realistic large-scale networks. The results show that our protocol presents a higher fairness index and yet it maintains a high level of bandwidth utilization efficiency compared to other approaches.



## 1. 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

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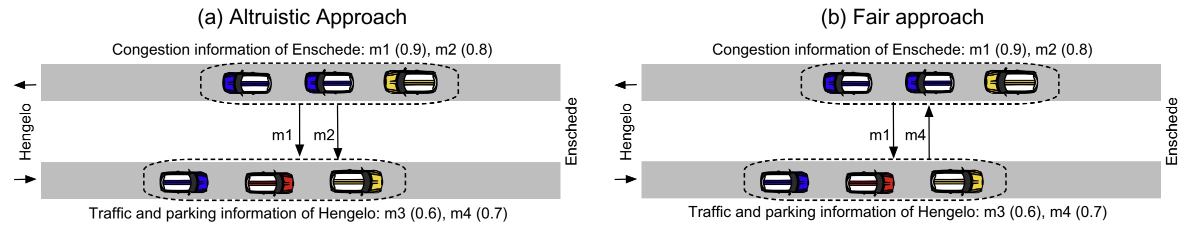


**Fig. 1.** Motivation for a *fair* data selection. In (a), only vehicles heading to the city of Enschede receive information, namely, congestion information about Enschede. A fair approach in (b) leads to a more even distribution of utility, providing traffic awareness to vehicles in both road directions.

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 Fig. 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 enough time or available 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.

The novelty of this work lies in addressing both problems of controlling the network load and selecting data in a road environment where vehicles have conflict of data interests. We present 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]. In [7], we have shown the capability of FairAD to control the network load while selecting messages with high utility and fairness to the neighborhood. This work complements [7] with the following contributions:

– Demonstration of the applicability of FairAD by giving example of utility functions for two TIS applications: (i) parking-related and (ii) traffic information applications. We additionally study the effects when both applications are considered simultaneously in our performance evaluation.
– Real-world experiments with two vehicles moving in opposite directions on a highway at high speeds. We validate the behavior of FairAD and other data selection approaches and study aspects such as the average connectivity time, transmission range achieved, packet loss and throughput.
– Validation of FairAD and other data selection approaches with simulations in large-scale networks. In particular, as urban scenario, we take a real map fragment from the Manhattan area in New York City, USA, including the shape of buildings that are used to model radio obstacles.

The remainder of this paper is organized as follows. In Section 2, we outline relevant related works and motivate the contribution of this work. Section 3 details the functioning of FairAD. In Section 4, we present example of two TIS applications along with their utility functions. The validation of FairAD is presented in Section 5. Finally, Section 6 concludes this paper.

## 2. 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 [8] 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 [9]. Similar to this work is [10], where authors consider the average system information age to maintain up-to-date state information among all nearby vehicles. In [11], a Peer-to-Peer (P2P) approach is introduced to address the problem of popular content distribution (PCD) in VANETs when a file is broadcast by roadside units (RSUs) to vehicles. Vehicles cooperate by exchanging data and complementing their missing packets. In [12], PrefCast is proposed. The protocol focuses on a preference-aware content dissemination that targets on maximizing the user's satisfaction in terms of content objects received. When a node meets neighboring users for a limited contact duration, it disseminates the set of objects that can bring possible future contacts a high utility. Although not explicitly defined in a general utility function, the Road Information Sharing Architecture (RISA) is presented in [13]. The architecture comprises a distributed approach to road condition detection and dissemination for vehicular networks. A Time-Decay Sequential Hypothesis Testing (TD-SHT) approach is used to combine event information from multiple sources to increase the belief of such events. Finally [14] 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 [15] 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 [16]. 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. Later in [17], authors present a generic framework for describing the characteristics of content exchange among nodes in Delay Tolerant Networks (DTNs). A distributed information popularity measurement is included and the pairwise interaction of nodes is modeled as a bargaining problem.

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 [18–20]. 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 [21] determines the data rate of each vehicle based on the application utility of each message in the transmission queue. Similarly [22] 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) [23]. 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 an ad hoc network, the PeerTIS [24] builds a peer-to-peer overlay over the Internet by means of a 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.

## 3. 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. The protocol complete stack comprises the Wireless Access in Vehicular Environments (WAVE) standard [25] and is shown in Fig. 2. Each application defines its own utility function and, thus, a utility value for each message sent down to lower layers. FairAD is then placed right below the application layer in order to intermediate and organize the order of these messages before being broadcast in the neighborhood.

### 3.1. 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.

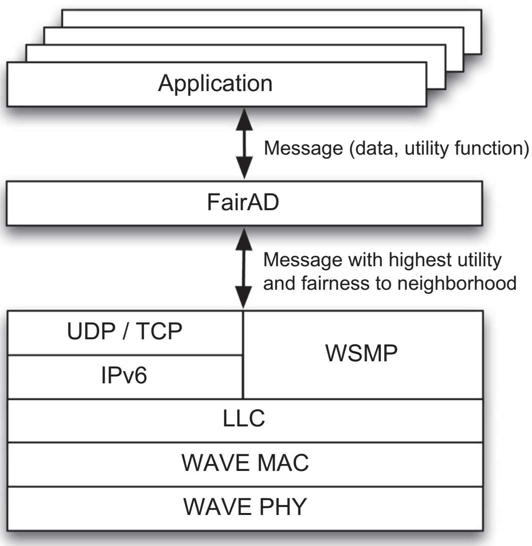


**Fig. 2.** The protocol stack overview.

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:

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

where $z_k^i$ with $k = 1,2,\ldots,l$ are the functions of each type of contextual information $k$ for vehicle $v_i$ weighted by parameters $\alpha_k$. These functions are normalized with values falling in a predetermined interval, e.g. [1,2]. The application is responsible for defining how these functions are combined in $u_{ij}$.

### 3.2. 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 [26] 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 [26] 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,

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

where $u_{ij}$ is given by (1). In matrix $U$, the utility value for each pair $(v_i, m_j)$ is given. There are $n$ potential 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 a 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 Eq. (1)), thereby affecting $c_i$. For example, when a vehicle moves from one geographical region to another or when a message becomes old. Fig. 3 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 speed, distance to message's region and message age (detailed in Section 4.2). 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.

The data selection process defines in a distributed manner the next message each vehicle 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 $\delta$ 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: $J \leftarrow \{0, 1, \ldots, n\}$
3: **while** $U \neq \emptyset$ **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: $\quad\quad P \leftarrow \left(\frac{r}{r_{max}}\right)$
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*

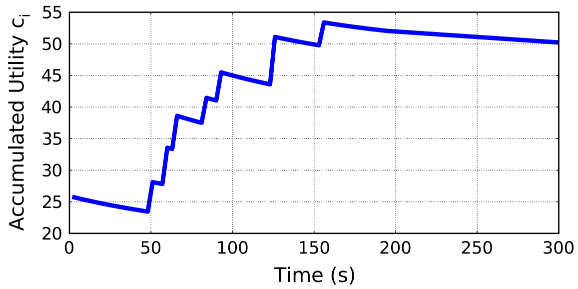


**Fig. 3.** Example of the accumulated utility ($c_i$) concept for a random vehicle moving in Manhattan, New York City, USA.

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 $O(n^2)$.

### 3.3. 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. As proposed in the ATB architecture 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 3.1. 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 3.2 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 $S$:

$$S = \max\left\{0, \left(1 - \frac{\text{SNR}}{\text{max.SNR}}\right)^2\right\}. \tag{4}$$

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

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

In order to give higher weight to metrics $K$ and $S$, factor $\omega_C \geqslant 1$ 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 $\omega_I$. 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.

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

The overview of ATB is shown in Fig. 4. In this example, vehicle $v_1$ sends message $m\_v_1$ with both lower $P$ and $C$ values because of the high message's priority and currently free channel. As time goes by, vehicles $v_2$ and $v_3$ find the channel busy. Due to a difference in their message priority, their transmissions are switched in time because of the higher priority given to message $m\_v_3$.

### 3.4. Adaptive periodic protocol

We propose an adaptive protocol that continually reevaluates the next data message to be sent and its

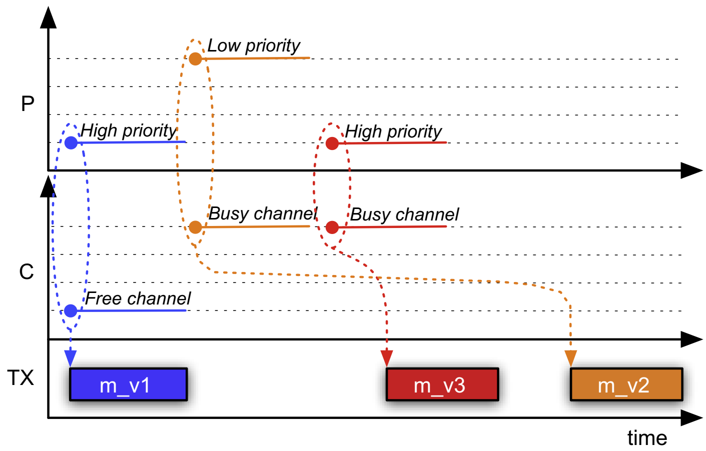


**Fig. 4.** Overview of ATB.

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 3.2 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 messages carried by vehicle $v_i$, i.e., subset $U_i$, multiple times without repeating the messages chosen in each iteration until the maximum list size is reached. However, further study is required to determine the best criteria to select messages when exceeding the maximum limit size.

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 [25], 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 $\omega_I = 1$ for $I_h$. As hello messages are equally important, $\omega_I = 1$ guarantees that only the channel quality $C$ is taken into account.

The complete protocol diagram is shown in Fig. 5. The upper part of the diagram shows the process of scheduling 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 and rescheduling messages if new data is available in the neighborhood as indicated by 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. When rescheduling, the new interval defined refers always to the last time a message was sent, thereby respecting the condition $I \in [I_{min}, I_{max}]$. Since hello messages are sent at a low frequency, i.e., at least 1 Hz, this measure does not incur excessive additional processing.

## 4. Applications

In previous work [3,7], we have considered basic utility functions with contextual information that may be common to a variety of applications. In the following, we elaborate on the utility functions of two specific basic applications: one related to (i) parking information; and another related to (ii) traffic information. In addition to evaluating FairAD with more realistic functions, we are interested in evaluating the impact of running both applications simultaneously.

These functions return values that fall in the interval [1,8], which provides enough room for utility disparity

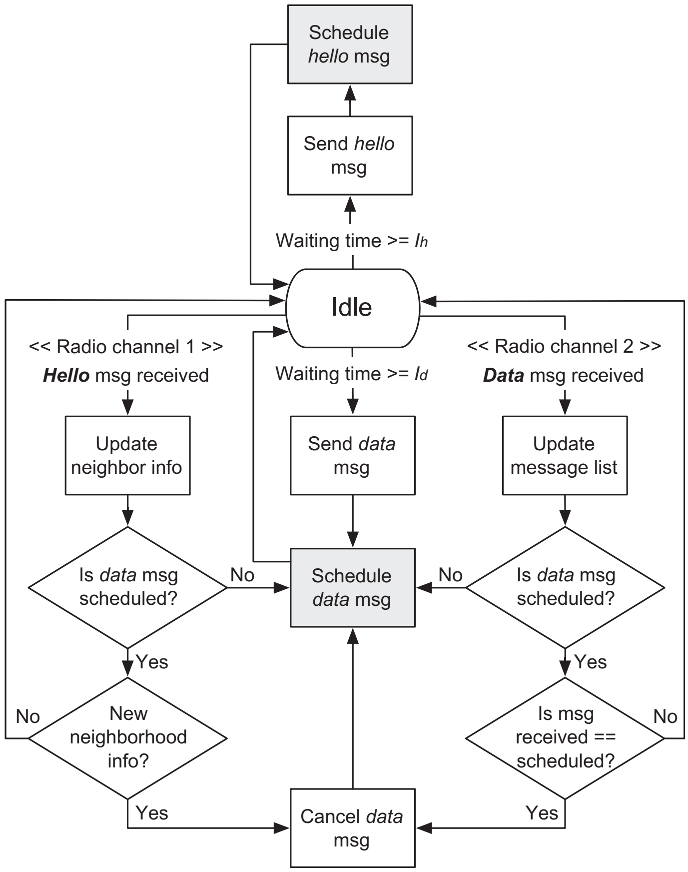


**Fig. 5.** FairAD protocol diagram.

between vehicles depending on their mobility and data context. Also, we choose multiplication as the means to combine different parameters in the utility functions in order to tighten their dependence and allow for a wider variety of values between different vehicles' context. Although different results can be expected when different contextual information and parameters are considered by an application, we argue that the contextual information that we propose may be incorporated in more complex applications of each type alongside other factors.

### 4.1. Parking information

We propose a parking related application that disseminates information about the parking places currently available in a city. To this end, we propose the use of the driver's intention to park the vehicle and the age of the parking information.

The utility function $u^p_{ij}$ is defined as:

$$u^p_{ij} = \begin{cases} 1 & \textbf{if } \text{the vehicle will } \textit{not} \text{ park;} \\ 2\ z^i_1(m_j)\ z^i_2(m_j). & \textbf{if } \text{the vehicle will park.} \end{cases} \quad (8)$$

$u^p_{ij}$ returns a value that falls in the interval [1,8], where both contextual knowledge functions $z^i_1(m_j)$ and $z^i_2(m_j)$ return values in the interval [1,2]. Effectively, vehicles that have the intention to park always receive higher values, namely, from the interval [2,8]. $z^i_1(m_j)$ and $z^i_2(m_j)$ are defined as follows:

*Distance to vehicle's parking destination ($z^i_1(m_j)$):*

$$z^i_1(m_j) = 2 - \frac{d^P_i(c_{m_j})}{5000} \quad (9)$$

where $d^P_i(c_{m_j})$ is a function which calculates the distance in meters between the vehicle's final parking destination and the coordinates of the parking place where the message was generated $c_{m_j}$. We assume that only parking information up to 5 km of distance are interesting for a vehicle: $d^P_i(c_{m_j}) \in [0, 5000]$, based on location-based service requirements defined in [27]. With distances farther than 5000, $z^i_1(m_j)$ is given the minimum value of 1.

*Data age ($z^i_2(m_j)$):*

$$z^i_2(m_j) = 1 + 0.99^{t_{mj}} \quad (10)$$

where $t_{mj}$ is the time elapsed since the message's generation time. Effectively, this function return values near the minimum value of 1 when $t_{mj}$ is close to 300 s.

### 4.2. Traffic information

We additionally propose a traffic related application that disseminates information about the current traffic situation in the city. Each vehicle periodically generates messages with their own speed and geographical coordinates. By sharing these messages, the speed profile of different regions of the city can be built. Although data aggregation could certainly be used to merge different messages as proposed in [28], this is out of the scope of this paper. We rather concentrate here on combining the vehicles's speed, distance, and age of information into a common utility function.

The utility function $u^T_{ij}$ is defined as the product:

$$u^T_{ij} = z^i_2(m_j)\ z^i_3(m_j)\ z^i_4(m_j). \tag{11}$$

$u^T_{ij}$ returns a value that falls in the interval [1,8], where each contextual knowledge function returns values in the interval [1,2]. $z^i_2(m_j)$ is used as defined previously for the parking information application, whereas $z^i_3(m_j)$ and $z^i_4(m_j)$ are defined as follows:

*Distance to vehicle* ($z^i_3(m_j)$):

$$z^i_3(m_j) = 1 - \frac{\left(d^T_i(c_{m_j})\right)^2}{6,245,000} + \frac{d^T_i(c_{m_j})}{1249} \tag{12}$$

where $d^T_i(c_{m_j})$ is the distance between the current vehicle's position and the coordinates $c_{m_j}$ where the message was generated. This function forms an inverted parabola with roots at points 0 and 5000 in the $x$-axis. On the one hand, messages containing information regarding distances immediately close to the vehicle are not interesting, since the driver may be aware of the traffic situation without resorting to information from other vehicles. On the other hand, information regarding excessively long distances can become outdated or can be unimportant if the vehicle never actually reach that region. Therefore, we define that distances near the center point 2500 in the $x$-axis return the highest values. We assume that only traffic information up to 5 km of distance are interesting for a vehicle: $d^T_i(c_{m_j}) \in [0, 5000]$, based on road congestion information requirements defined in [27]. With distances farther than 5000, $z^i_3(m_j)$ is given the minimum value of 1.

*Traffic speed* ($z^i_4(m_j)$):

$$z^i_4(m_j) = 2 - \frac{s_{m_j}}{36} \tag{13}$$

where $s_{m_j}$ is the speed of the vehicle that generated message $m_j$. We assume that speeds vary in meters per seconds in the interval $[0, 36]$. In this function, more importance is given to low speed values, as these indicate potential traffic jams in the city. Speeds higher than 36 m/s are given the minimum value of 1.

## 5. Performance evaluation

The performance evaluation of FairAD is carried out by means of both real-world experiments and simulations. Our goal is twofold: (i) verify the correctness and feasibility of employing different data selection mechanisms in real-world environments and (ii) compare FairAD's data selection in large scale simulation scenarios against other data selection approaches. The following data selection mechanisms are used as comparison:

(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 [29]. 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.

Our evaluation considers the following metrics:

- *Jain's fairness index:* calculated each time a vehicle selects and sends a data message; defined as $\left(\sum_i^h c_i\right)^2 / \left(h \sum_i^h c_i^2\right)$ (see [30]), 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 message 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 to which the message relates. The area radius is defined as: $\frac{1}{4}\sqrt{x^2_{max} + y^2_{max}}$, where $x_{max}$ and $y_{max}$ are the maximum x and y cartesian values of the scenario being considered.

### 5.1. Real-world experiments

In our real-world experiments, we use two vehicles equipped with a 802.11p gateway. The Atheros AR5413 802.11a radio is used with a modified driver to comply with 802.11p standard in terms of frequency band, channel width, and bit rate. We implement the FairAD protocol and the other data selection methods used for comparison in a Perl script. The standard socket library is used to broadcast UDP packets in their maximum size before fragmentation, namely, 1472 bytes. In total, around 2312 bytes are sent when taking into account extra overhead in the MAC and PHY layers. Since the experiments consist of only two vehicles, the parameters related to channel load used by FairAD are unnecessary. Specifically, the $r_{max}$, $\delta$, and $\omega_C$ parameters are omitted. Therefore, we focus on the priority of messages with $\omega_I = 0$. The experiment parameters are summarized in Table 1.

Our scenario consists of two vehicles driving in opposite directions in one piece of the A35 highway that links the cities of Enschede and Hengelo in The Netherlands. During the day of experiments, the weather humidity was 92%

**Table 1**
Experiment parameters.

| | | |
|---|---|---|
| Physical layer | Frequency band | 5.88 GHz |
| | Bandwidth | 10 MHz |
| | Tx power | 20 dBm |
| Link layer | Bit rate | 6 Mb/s |
| FairAD | $I_{min}$ (hello msg) | 1 s |
| | $I_{max}$ (hello msg) | 1 s |
| | $I_{min}$ (data msg) | 30 ms |
| | $I_{max}$ (data msg) | 60 s |
| | $\omega_I$ (data msg) | 0 |
| Scenarios | Relative speed | ~225 km/h |
| | Data message size | 2312 bytes |
| | Initial # messages | 250 |

with temperature around +4 °C. Each vehicle begins in a junction point located near one of the two cities and drives 5.6 km until it reaches the other junction point. The average relative speed between the vehicles is 225 km/h. In total, this process is repeated 12 times, where 4 times is reserved for experiment 1 and 8 times for experiment 2 (2 times for each data selection). Each experiment is described as follows:

- *Experiment 1:* consists of one sender and one receiver only, without any sort of data selection. The sender broadcasts messages continuously with no interval between the messages. Our goal is to evaluate how much data can be received correctly when two vehicles are moving at high speeds in opposite direction.
- *Experiment 2:* consists of comparing each data selection method. All methods are run in the same protocol as shown in Fig. 5. Hello messages are sent at a fixed rate of 1 Hz and data messages are sent in the interval ∈[0.030, 60] s, as proposed in [6]. Each vehicle includes its updated accumulated utility value $c_i$ in each message transmitted and keeps track of the accumulated utility of the other vehicle in order to make data selection decisions. After each messages is received, the priority of the message scheduled is updated and the waiting interval is defined according to each data selection method. To provoke a conflict of interests and test the behavior of each data selection method, we define that each message worths 10 of utility to one vehicle and only 1 to the other. Each vehicles begins with 250 messages to be exchanged.

The results that are common to both experiments are averaged and shown in Table 2. Due to the high relative speed between the vehicles and the average of 254.1 meters of transmission range achieved, the average time of connectivity is limited to only 7.62 s. In experiment 2, the throughput achieved is lower than with experiment 1 due to the minimum interval of 30 ms between every two transmissions performed by a vehicle. The packet loss is also lower with experiment 2, since one vehicle only begins exchanging data with another after it has correctly received a hello message. Fig. 6 shows a sample of the received signal strength when running experiment 1. In this sample, the connectivity time is around 10 s with the strongest peak lying in the center around 5 s when the vehicles pass by each other.

**Table 2**
Experiment results.

| | Average | Standard deviation |
|---|---|---|
| Connectivity time | 7.62 s | 1.31 s |
| TX range achieved | 254.1 m | 25.15 m |
| Messages per sec. exp. 1 | 40.21 | 1.47 |
| Messages per sec. exp. 2 | 17.17 | 1.40 |
| Throughput exp. 1 | 743.8 kb/s | 27.22 kb/s |
| Throughput exp. 2 | 317.6 kb/s | 25.98 kb/s |
| Packet loss exp. 1 | 75.39% | 0.55% |
| Packet loss exp. 2 | 19.42% | 11.95% |

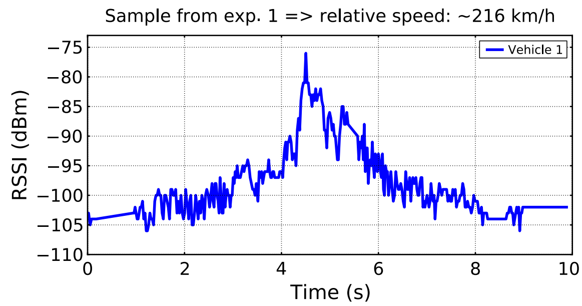


**Fig. 6.** The evolution of the received signal strength during one data exchange in experiment 1.

In Fig. 7, we compare the behavior of each data selection method along time during data exchanges performed in our experiments. Since one vehicle receives 10 worth of utility and the other only 1, when employing Altruistic only one vehicle broadcasts messages (Fig. 7(a)). For this reason, only vehicle 1 accumulates utility gains during the data exchange. With an opposite behavior, Max–min aims always to compensate differences in utility gains to achieve an equal utility gain in both vehicles as shown in Fig. 7(c). FairAD aims at not only fairness but also efficiency in terms of the total utility distributed. Therefore, the compensation is limited and a compromise between both goals is achieved along time (Fig. 7(b)). Finally, when no selection mechanism is used, a poor result can be achieved (Fig. 7(d)). In particular, the latter result represents the worst case in terms of efficiency, since no selection chooses messages with the lowest IDs, which in this case are the ones with lowest utility. Since the results are shown from the point of view of vehicle 1, there are some negative fluctuations in the accumulative utility of vehicle 2 ($c_2$). This is explained by the fact that vehicle 1 keeps track of $c_2$ by increasing it every time a new message is sent. Since not every message is received correctly by vehicle 2, $c_2$ is corrected every time vehicle 2 sends a new hello message.

Fig. 8 shows the average results in terms of fairness index and utility per message received for all runs of experiment 2. Altruistic clearly presents the best result in terms of efficiency at the cost of having the worst fairness index. Conversely, Max–min achieves the best result in terms of fairness and a poor result in terms of efficiency. The dashed lines in Fig. 8(a) indicate the minimum and maximum

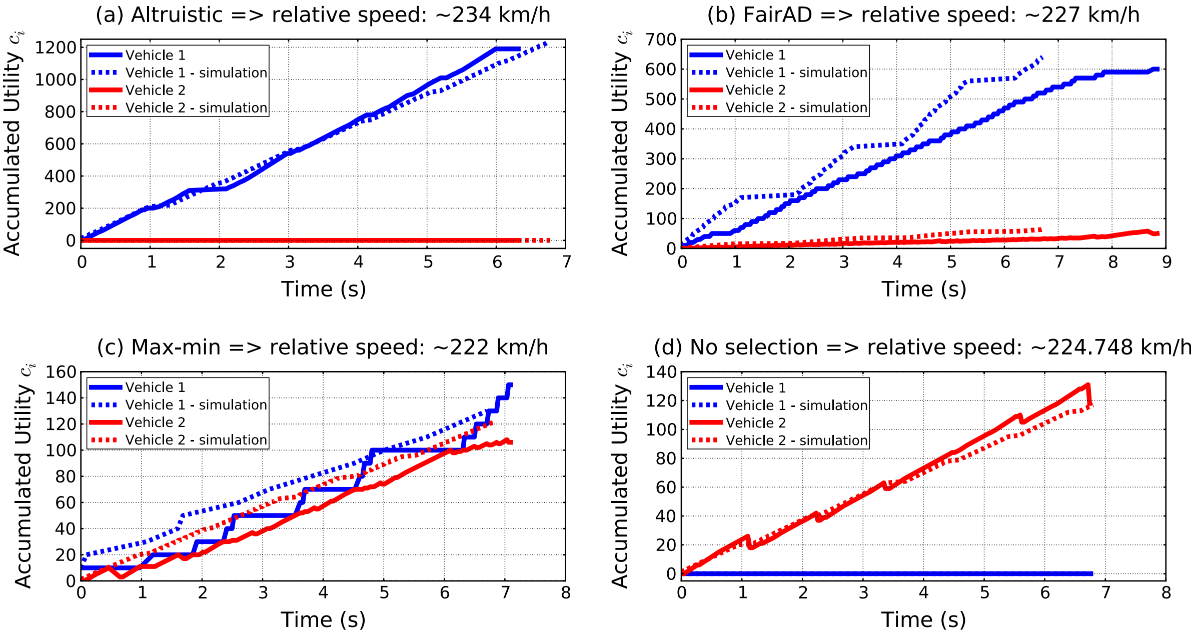


**Fig. 7.** The behavior of each data selection method over time in both real-world experiments and simulations from the point of view of vehicle 1.

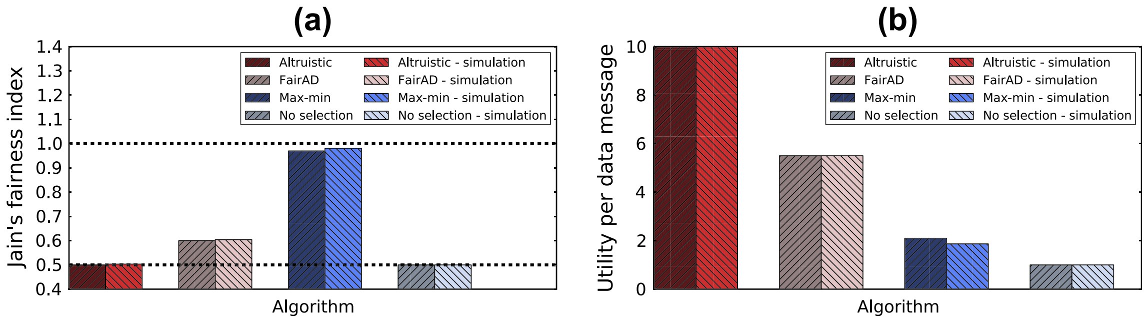


**Fig. 8.** The Jain's fairness index and utility per message received averages for both real-world experiments and simulations.

achievable values for the fairness index when only two vehicles are present.

All results above are in line with the expected behavior of each method, given their individual goals. In both Figs. 7 and 8, we additionally verify that our simulation implementation represents a proper matching of the real-world experiments. This serves to strengthen the confidence in using our simulation implementation for large-scale scenarios as described in the next section. All simulation parameters are adjusted to match the real-world experiment results. In particular, the minimum transmission interval $I_{min}$ is set to 50 ms in order to consider the additional overhead introduced by the application layer in the gateway before sending down broadcast messages. The only difference between the simulation parameters used to validate our real-world experiments and the ones used in our large-scale simulations is with regard to the power level used. For the validation of our real-world experiments, a power level of 20 dBm was used to match the power level used by our gateway. However, for the sake of scalability, a lower transmission range was preferred in our larger-scale simulations, as summarized in Table 3.

## 5.2. Simulation

In our simulations, we evaluate the impact on each data selection method when considering both applications defined in Section 4 in large-scale scenarios. We use the Veins[1] framework [31] 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

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

**Table 3**
Simulation parameters.

| | | |
|---|---|---|
| Physical layer | Frequency band | 5.88, 5.89 GHz |
| | Bandwidth | 10 MHz |
| | Transmission range | ~100 m |
| | Tx power | 10 mW |
| | FSPL exponent $\alpha$ | 2.5 |
| | Obstacle model | Defined in [32] |
| | Receiver sensitivity | −90 dBm |
| | Thermal noise | −110 dBm |
| | Bit Error Rate (BER) | Based on [33] |
| Link layer | Bit rate | 6 Mb/s |
| | CW | [15,1023] |
| | Slot time | 13 μs |
| | SIFS | 32 μs |
| | DIFS | 58 μs |
| FairAD | $r_{max}$ | 5 |
| | $\delta$ | 0.1 |
| | Max. SNR ($S$) | 50 dB |
| | Max. # neighbors ($N$) | 50 |
| | $\omega_C$ | 2 |
| | $I_{min}$ (hello msg) | 1 s |
| | $I_{max}$ (hello msg) | 5 s |
| | $\omega_I$ (hello msg) | 1 |
| | $I_{min}$ (data msg) | 50 ms |
| | $I_{max}$ (data msg) | 60 s |
| | $\omega_I$ (data msg) | 0.5 |
| Scenarios | Data message size | 2312 bytes |
| | Initial # messages | 5 |
| | Max. msg list size in hello | 100 |
| | # runs | 30 |

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 3. 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 hello and data 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 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 [0.05, 60], where the minimum of 50 ms is used to match our real-world experiments, as explained in the previous section. We also set a different value to $\omega_I$ for each message type, namely, $\omega_I = 1$ and $\omega_I = 0.5$ for hello and data messages, respectively. $\omega_I = 0.5$ 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.

In the following sections, we present the results of running each data selection method in both urban and highway scenarios. We consider the following behavior for each combination of applications proposed:

- *Parking:* each vehicle begins with 5 messages containing information about fictitious parking places that they have passed by before the beginning of the simulation. The locations of these parking places are defined as the coordinates of 500 m towards the opposite heading direction vector of the vehicle. We also define that half of the vehicles will eventually park in their final geographical coordinates of their mobility traces. Finally, the start age of messages is defined as a random number in the interval [0, 300] s.
- *Traffic:* each vehicle begins with zero messages. Instead, a new message is generated by each vehicle at every 5 s containing its current position, speed, and generation time.
- *Both:* both applications are included in the simulation. Each vehicle begins with 5 messages containing parking information and generates traffic information messages at every 5 s.

### 5.3. Urban scenario

For urban scenario, we select a map fragment from Manhattan, New York City, USA. This segment has an area of $1.5 \times 2$ km$^2$ and was retrieved with OpenStreetMaps.[4] The average density at a random time instant is 50 vehicles/km$^2$. Fig. 9 shows the complete map fragment considered, where buildings represented by dark rectangles serve as radio obstacles modeled as described in [32]. Simulations for this urban scenario consist of 20 runs of 300 s.

Fig. 10 shows the histogram of the connectivity time between every pair of vehicle in our urban scenario. In this urban setting, the connectivity time can vary from a few seconds to tens of seconds, depending on whether vehicles have a similar route. Notably, more than 4% fall in connectivity times that are lower than 3 s, which could be explained by the presence of buildings serving as obstacles in our scenario.

Fig. 11(a) shows the results when applying the Jain's fairness index. As expected, FairAD and Max–min present the highest fairness index values, whereas Altruistic consistently presents lower values in all combinations. Although Max–min gives more priority to maximizing fairness, FairAD achieves higher fairness index in the parking application. This can be reasoned by the high gap in utility among vehicles depending on whether they will eventually park or not. For this reason, Max–min is not always able to compensate the low utility of all vehicles in the neighborhood. In contrast, FairAD manages to spread messages with higher utility more quickly and, in this particular scenario, is able to achieve a higher fairness index on average. The approach with no selection presents variable results, since it only considers the messages' IDs as criteria for selecting data to broadcast.

In terms of efficiency, Fig. 11(b) presents the results for the utility per message received. In all cases, Altruistic and

[4] www.openstreetmap.org

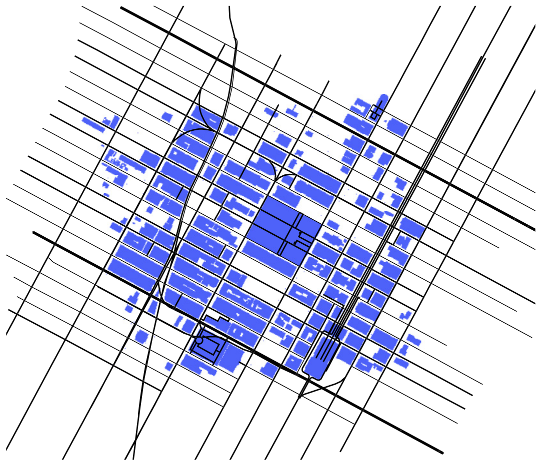

**Fig. 9.** Urban scenario: map fragment of Manhattan, New York City, USA.

FairAD achieve higher efficiency compared with Max–min and no selection. Notably, FairAD outperforms Altruistic in the parking application. To explain this behavior, we have further analyzed the exchange of messages of both methods. The reason for such difference lies in the fact that Altruistic only prioritizes the total utility gain of all neighbors as a whole. Especially with such variability in the utility that each vehicle gains in this scenario, some vehicles simply do not receive any new message, which hinders the dissemination of certain messages that could be of higher utility for other vehicles encountered later in the city. Such behavior has been already previously observed in our results in [4].

The delay is generally lower for all methods that consider utility when exchanging messages, as shown in Fig. 11(c). The delay values are higher with the parking application, since we assign random start age values in the beginning of the simulation taken from the interval [0,300].

Fig. 11(d) shows the percentage of messages received by a vehicle for each application. We can observe that traffic related information is spread more quickly when employing data selection methods due to its higher relevance to most vehicles on the road. On the other hand, since parking information contain lower messages IDs in the simulation, more messages of this type are spread with the approach with no selection.

Finally, Fig. 12 highlights the differences between each data selection method by showing the map of information received by a random vehicle when running both applications. Since messages with higher utility values are gathered with both Altruistic and FairAD, they present higher utility per message received compared with Max–min and no selection. Another point worth noting is that the information received with Altruistic and FairAD relates to coordinates that are closer to the vehicle's route, indicated with a solid line. In contrast, Max–min and no selection gather data related to farther locations, thereby providing lower utility to the vehicle. Notably, as previously mentioned, the approach with no selection collects more parking information compared with other approaches.

In summary, the goal of each data selection method directly influences the behavior of the data exchange performed in the neighborhood. Overall, FairAD achieves both high fairness index and efficiency. Also, the delay is notably lower for methods employing data selection.

### *5.4. Two-directional highway scenario*

The highway consists of a 1 km straight road with two lanes in each road direction. We select a moderate density of 20 vehicles/km/lane that contains both vehicles moving at high speeds, i.e., 120 km/h, and low speed traffic due to a small traffic jam in one of the road ends. For this scenario, in total 20 runs of 100 s are executed.

Fig. 13 shows the histogram of the connectivity time between every pair of vehicle in this highway scenario. Compared with our urban scenario, the connectivity time between vehicles is generally lower due to quicker encounters in the highway, with 80% being concentrated up to only 10 s of connectivity.

Fig. 14(a) shows the results when applying the Jain's fairness index. The results are similar to those presented in our urban scenario, where Max–min and FairAD achieve higher fairness index compared with Altruistic.

In terms of efficiency (Fig. 14(b)), the higher utility per message received achieved by FairAD when compared with Altruistic is evident, in this case, for both

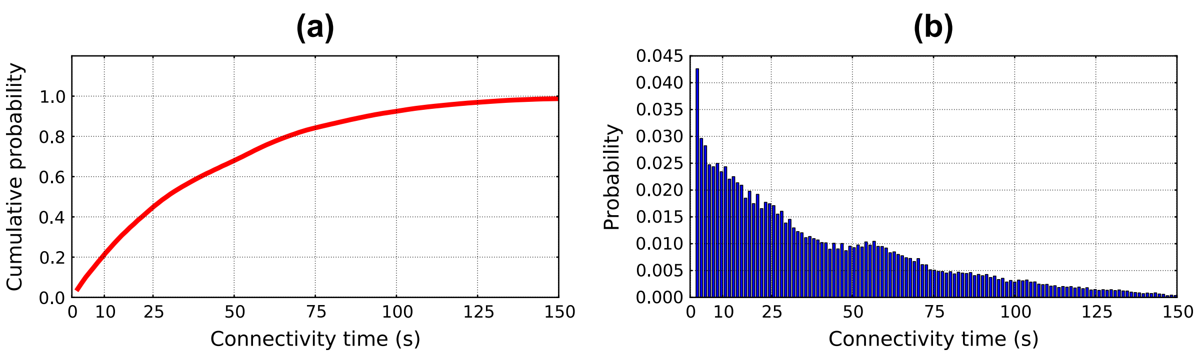


**Fig. 10.** The connectivity time histograms for the urban scenario.

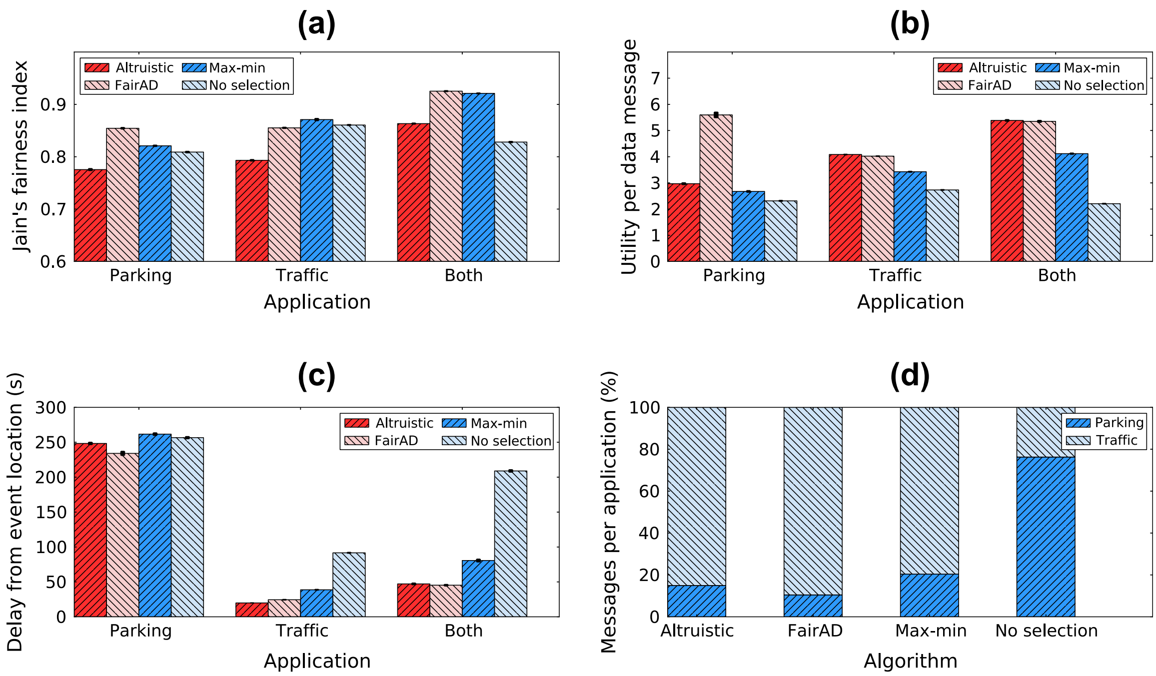


**Fig. 11.** Results with 95% confidence intervals for the urban scenario.

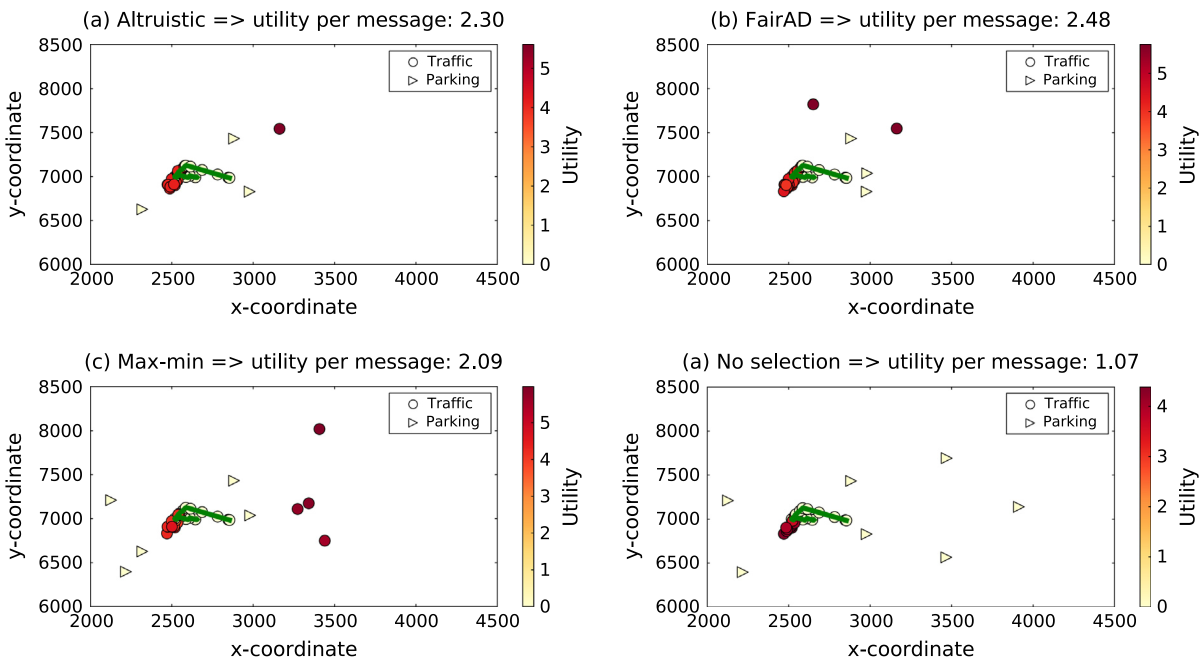


**Fig. 12.** Geographical map of the information received by a random vehicle in the urban scenario.

applications. Especially because of the presence of quicker encounters between vehicles, only few vehicles are benefited from the data exchange in some occasions with Altruistic, which hinders the dissemination of other messages potentially important to other vehicles further ahead on the road.

Similarly to what we observe with the urban scenario, the delay is generally lower when employing data selection mechanisms, as shown in Fig. 14(c). In particular, Max–min presents higher delay when running the parking application due to its inability to compensate differences in utility gain between vehicles in such quick encounters.

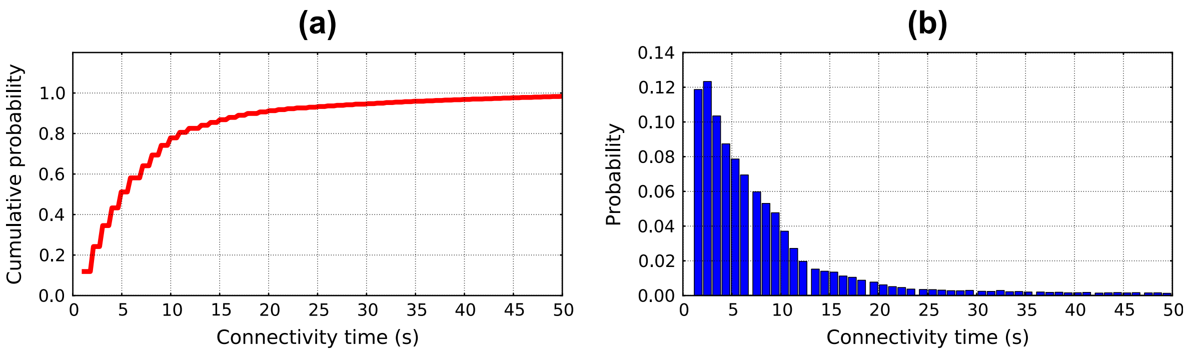


**Fig. 13.** The connectivity time histograms for the highway scenario.

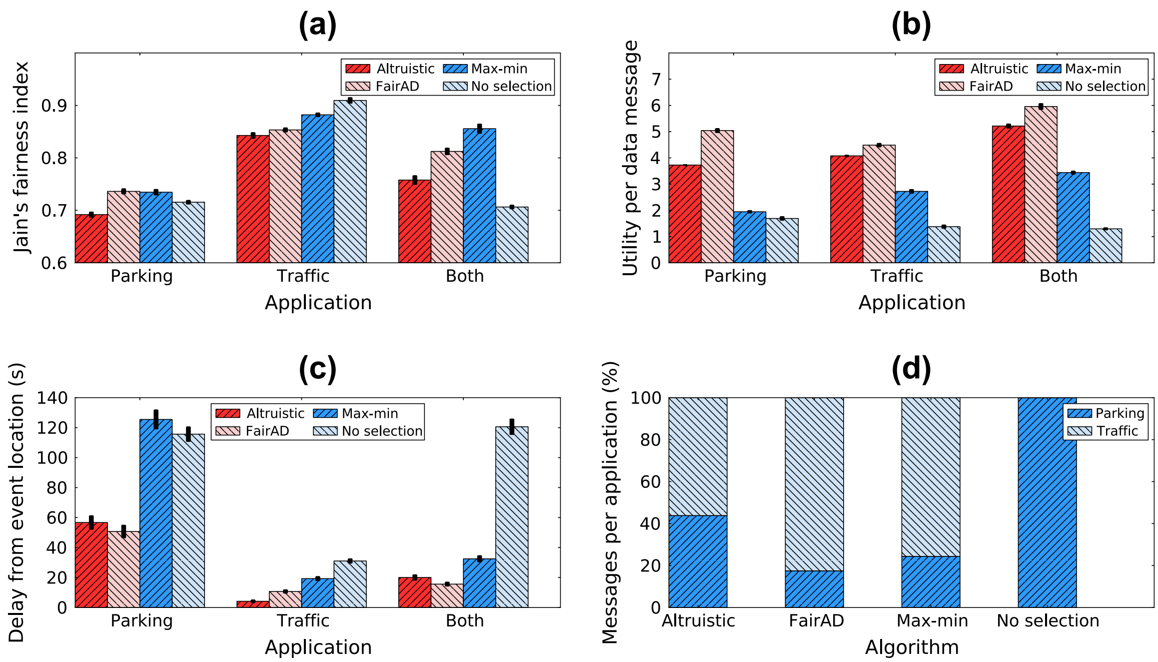


**Fig. 14.** Results with 95% confidence intervals for the highway scenario.

Fig. 14(d) shows the percentage of messages received by a vehicle for each application. The limited connectivity time between vehicles accentuates the priority given by the approach with no selection to disseminate parking information only.

Overall, the results follow a similar pattern to those presented for urban scenarios. However, because of the limited connectivity time present for data exchange, the differences between each method becomes more evident.

## 6. 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.

We verified the correctness of FairAD by means of real-world experiments. With a typical experiment set-up, we show that the connectivity time between vehicles moving at high speeds in opposite directions can be limited to a few seconds and considerably compromise the amount of data exchanged. Furthermore, 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 future work, we will investigate solutions for guaranteeing utility fairness not only among different neighbors but also between different applications. In addition, we plan to consider more complex applications that include further data processing such as data aggregation.

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