ROADNET: Fairness- and Throughput-Enhanced Scheduling for Content Dissemination in VANETs

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***Abstract*—The increasing demand for bandwidth by applications in Vehicular Ad-Hoc Networks (VANETs), combined with the increasing number of their users, stresses the importance of data dissemination schemes that strike a balance between network throughput and user fairness. Ensuring this balance is challenging in vehicular networks, which are characterized by a high dynamism of the network topology, volatility of inter-vehicular links, and heterogeneity of the exchanged content. For these reasons, we hereby introduce ROADNET, a cooperative content dissemination scheme for VANETs. Leveraging on the Software Defined Networking (SDN) paradigm, ROADNET provides a trade-off between network throughput and user fairness by exploiting the logical centralized control of SDN and the multichannel operation of the IEEE 1609.4 standard. Realistic simulation results show that our scheme outperforms prior works in terms of both throughput ($\approx 36\%$) and fairness ($\approx 6\%$), providing high channel load balance ($\sigma \approx 1\%$).**

I. INTRODUCTION

Infotainment services in VANETs are an essential part of the future delay-tolerant applications, and their provision imposes strict requirements on the efficiency of data dissemination [1]. The intermittent nature of the communication links, coupled with the highly variable density and speed of the vehicles, can hamper data dissemination and therefore deprive some users of receiving their requested service. Roadside Unit (RSU)-assisted Vehicle-to-Vehicle (V2V) dissemination strategies are effective, but cannot ensure reliable content dissemination alone. Sharing content among neighboring vehicles via V2V communications minimizes the rebroadcasting of the same content by the RSU, allows vehicles outside the coverage range of the RSU to be reached, and consents transmission of multiple content items at the same time without interference. On the other hand, Software-Defined Networking (SDN)-enabled VANETs have been proposed to increase vehicular networks' programmability so that routing, data dissemination, and scheduling strategies are adjusted dynamically to changing network conditions and user requirements [2] [3]. Thus, controllers placed at RSUs with support from V2V communications can provide significantly improved infotainment service delivery in SDN-enabled VANETs.

Another challenging dilemma concerning data dissemination is striking a balance between fairness and throughput. This contrast occurs because maximizing only the fairness among users leads to giving equal opportunities for transmissions, even to those users who have reduced communication capabilities or who would severely interfere with neighboring receivers. On the other hand, maximizing only the global throughput may lead to starvation of some users and therefore could hamper the fairness. Most of the existing cooperative data dissemination schemes focus only on either increasing the network throughput [3] [4] or ensuring fairness among users [5] [6]. Few studies investigated the problem of maximizing the throughput while guaranteeing fair access to the network resources [7] [8] and [9]. In [7], a Unified TDMA-based Scheduling Protocol for Vehicle-to-Infrastructure (V2I) communications is proposed to optimize the throughput for non-safety applications. To build this schedule, the RSU collects the necessary information such as channel state information and the speed of the vehicles within its range. Then, time slots are allocated to vehicles based on the weight function which consists of three weight factors: channel-quality, speed, and access category. While the first factor ensures maximization of the network throughput, the second one is used to ensure fairness between vehicles. However, this scheduling algorithm is designed for throughput-sensitive applications. Moreover, authors used only one RSU to evaluate its performances without specifying the mobility scenarios. Authors of [8] proposed BUFE-MAC which supports two communication modes: 1) the mesh-backbone-based mode where vehicles transmit packets in a multi-hop manner and 2) the infrastructure mode where vehicles directly exchange data with a fixed Internet gateway (RSU). The distance between successive RSUs is divided into n equal-sized segments. BUFE-MAC divides the cycle time into several time slots for vehicles in proper segment-accessing bandwidth. Each segment has the same opportunity to access the bandwidth. In addition, BUFE-MAC integrates the uplink and downlink transmissions in a single channel. In [9], authors addressed the starvation of users who request non-popular data items that are broadcast very few times. They considered a RSU that runs a scheduler and supports two channels, one for user requests and another for responses. Through the request channel, vehicles submit their requests which are inserted into the service queue of the RSU server. A fairness-friendly scheduling algorithm runs on the RSU, which then broadcasts the selected data item through the downlink response channel.

This paper proposes an SDN-based scheduling scheme with throughput and fairness enhancements for SDN-enabled VANETs. Our scheme, called ROADNET (faiRness and thrOughput-enhAnced scheDuling for conteNt dissEmination in VANETs), builds on two prior works [3] [10] and aims to improve the network throughput while maintaining fair opportunities for all vehicles. The main contributions of this paper are twofold:

- An SDN-based scheduling scheme which, through the control plane, gathers requests from vehicles moving within the communication range of the RSU and builds an optimized scheduling that strikes the balance between fairness and throughput,
- A multi-channel allocation strategy based on the IEEE 1609.4 protocol of the Wireless Access in Vehicular Environment (WAVE) protocol stack.

The rest of the paper is organized as follows: Section II presents the system architecture and highlights the work carried out in [3] which will be the baseline for our contribution. In section III, we detail ROADNET, the SDN-based scheduling scheme. We describe the different signaling messages (control plane) used to establish an optimized schedule striking balance between throughput and fairness. We detail as well our multi-channel allocation scheme based on the 1609.4 standard in WAVE. Sections IV and V present the simulation settings and performance analysis, respectively. Finally, Section VI concludes the paper.

II. SYSTEM ARCHITECTURE

A. System Model

In our envisioned scenario, vehicles drive in either urban or highway environments, characterized by the extensive presence of RSUs. The vehicles may be equipped with an On-Board Unit (OBU), which allows the vehicle to perform V2V and V2I communications. Both OBUs and RSUs transmit data according to the WAVE protocol stack, which encloses the Wave Short Message Protocol (WSMP), the IEEE 802.11p, and the IEEE 1609 protocols. The IEEE 1609.4 subprotocol controls the medium access over one Control Channel (CCH) and six Service Channels (SCHs). However two channels (SCH 172 and SCH 184) are reserved for future use and will not be considered in this work. Each OBU and RSU transmits network control messages on the CCH, and user application messages on the four SCHs. Every OBU in the scenario periodically broadcasts beacon messages called Basic Service Messages (BSMs) [11] on the CCH and uses the received BSMs to maintain an updated list of neighboring vehicles.

Every vehicle in the network can request and store pieces of information, which can be retransmitted to neighboring vehicles with single-hop V2V communications in a cooperative way. This information exchange is managed and optimized by a Software-Defined Networking Controller (SDNC), which is located in the fixed network infrastructure, close to the RSU. The controller periodically collects information about the status of the network and returns an optimized transmission schedule to the vehicles, computed in order to maximize network throughput and ensure fairness among users. The SDNC takes care of converting the policies of the SDN application modules into concrete actions to be enforced by the network users. From this viewpoint, our system can be represented as depicted in Figure 1, where the OBUs exchange signaling messages with the SDNC on the control plane through the CCH, and exchange application-layer messages on the data plane through the SCHs. The SDNC uses the SouthBound Interface (SBI) to send signaling messages to the OBUs and the NorthBound Interface (NBI) to communicate with application modules. These modules have the ability to program the underlying network through the NBI. In this architecture, the algorithms and techniques that provide efficient network transmission scheduling, traditionally tightly coupled with the network, can be enclosed in an SDN application module to provide flexibility, modularity, and programmability. In this work, we propose ROADNET as one possible SDN application module to provide optimal transmission schedules in terms of throughput and user fairness, and we assess its performances comparing them with another state-of-the-art scheduler [3].

B. Cooperative Data Dissemination (CDD)

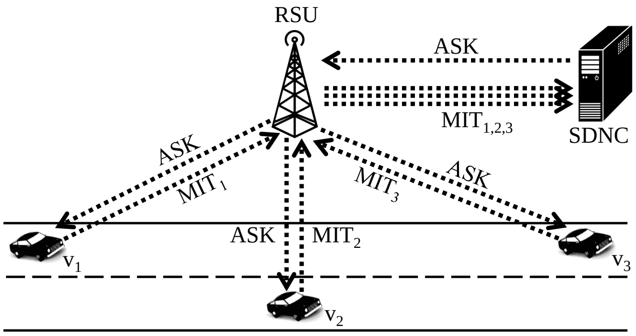
In [3], the authors propose a Vehicle-to-Everything (V2X) transmission scheduling algorithm for SDN-based VANETs, which aims at maximizing network throughput using graph theory. In their scenario, SDN-enabled vehicles drive on a three-lane highway and their OBUs can benefit from the centralized SDNC coordination when they are located in a geographical area called *service area*. Every control message is exchanged on the CCH, while the Infrastructure-to-Vehicle (I2V) and V2V communications take place on SCH1 and SCH2, respectively. The RSU periodically collects control messages containing information about the VANET's topology and about the content items that are requested and cached by the OBUs. Using this information, the RSU generates a set of potential V2X transmissions.

In their approach, the potential transmissions are modeled as weighted vertices of a single undirected graph, and those vertices that represent conflicting transmissions (i.e. that cannot be scheduled at the same time) are connected by an unlabeled edge. The weight of each vertex represents the transmission's priority, and it is computed aiming at maximizing the total network throughput. In particular, the vertex's weight increases as the receiver's speed increases and decreases as the receiver's distance from the service area border increases.

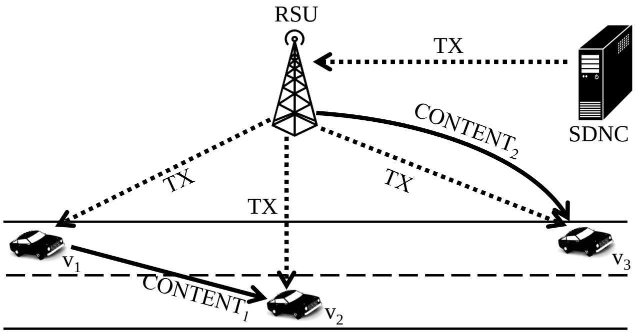
Once the weighted graph is built, the optimal transmission schedule is obtained by solving the associated Maximum Weighted Independent Set (MWIS) problem. The goal of this problem is to find the subset of nodes that are not connected by any edge and that have the highest weights sum. Since the MWIS problem is NP-hard, the authors apply a linear algorithm [10] to approximate the solution. The outcome of this algorithm is a set of non-conflicting transmissions that will occur on SCH1 for I2V communications and on SCH2 for V2V communications.

III. ROADNET: AN SDN-BASED SCHEDULING SCHEME

Our proposed scheduling scheme defines a control-plane operational mode to collect the needed network control information and a novel scheduling algorithm, which aims at



(a) ASK Phase



(b) TX Phase

Fig. 1. An example of message exchange during ROADNET's ASK and TX Phases. The dashed arrows represent the transmission of control-plane messages on the CCH. The solid arrows represent the transmission of V2V or I2V data-plane messages on SCHs. The two CONTENT messages are scheduled on different SCHs, therefore there is no interference at v_2.

TABLE I
ROADNET MESSAGES

Message	Source	Description
ASK	RSU	It informs the OBUs that ROADNET is entering the ASK Phase and that they should return a well-formed MIT message.
MIT	OBU	It contains the IDs of the OBU's neighboring vehicles, cached content items, and requested content items.
TX	RSU	It contains the transmission schedule, expressed as a list of vehicles IDs, each one associated to a content item ID and a SCH.
CONTENT	Any	It contains a certain piece of information as instructed by the RSU schedule.

balancing network throughput and user fairness in multi-channel communications. First, we detail the control and data planes of ROADNET in Section III-A. Then, we describe the scheduling algorithm in Section III-B.

A. Control- and Data-Plane Operation

ROADNET is structured in three cyclic phases: the ASK Phase, the Schedule Computation Phase, and the TX Phase. Table I describes the different control- and data-plane messages that are exchanged by the scheme, while Figure 1 illustrates how they are exchanged during the different phases.

1) ***ASK Phase:*** When this phase begins, the RSU broadcasts an ASK message and immediately starts collecting MIT messages from the OBUs. Each OBU that receives an ASK message from the RSU builds a well-formed MIT message using local information and unicasts it back to the RSU. The RSU uses the information contained in the received MIT messages to compute the *network state information*, which is an approximation of the real-world VANET topology, plus a map of the content items that have been requested and cached by each OBU. After T_{ASK} seconds from the beginning of the phase, the RSU stops accepting MIT messages and ROADNET advances to the Scheduling Computation phase.

2) ***Scheduling Computation Phase:*** During this phase, the SDN scheduling application will use the *network state information* to produce a transmission schedule for V2V and I2V communications that satisfies a set of Quality of Service (QoS) requirements. For the sake of flexibility, the SDN scheduler can implement several different scheduling algorithms in this phase, such as Round-Robin, Most Requested First, CDD, ROADNET scheduling algorithm, etc. When the chosen scheduler completes the computation of the transmission schedule, ROADNET advances to the TX phase.

3) ***TX Phase:*** As this phase starts, the RSU builds a well-formed TX message using the transmission schedule computed by the Scheduling Computation phase and then broadcasts the message to all the OBUs in range. Every vehicle that receives the TX message checks if its ID is contained in the list and, if so, encapsulates the suitable content in a CONTENT message and broadcasts it immediately after on the specified channel. The vehicles that have not been selected for transmission will listen on a SCH, according to the information contained in the received TX message. When a vehicle receives a CONTENT message of its interest, it stores it in a temporary memory called *cache* for T_{INFO} seconds. Caching content is fundamental in the proposed approach, as it allows content dissemination through V2V communications. After T_{TX} seconds from the beginning of the Scheduling Computation phase, the RSU deletes the *network state information* and ROADNET restarts from the ASK phase.

B. Scheduling Algorithm

The goal of the ROADNET scheduling algorithm is producing a balanced transmission schedule for simultaneous V2V and I2V communications over four SCHs. This scheduling algorithm relies on a Multi-Layered Conflict Graph (MLCG) structure and is composed of two steps:

1) First Step: Master Conflict Graph Creation: The first step consists of creating an undirected graph G called *master conflict graph*, in a similar way as done in [3]:

a) ***Compute the Service Weights:*** Each vehicle has a different service priority, and in order to guarantee fair access to the network resources, this priority should take into consideration how many content items a certain vehicle has received in the past, according to its demand. Therefore, we

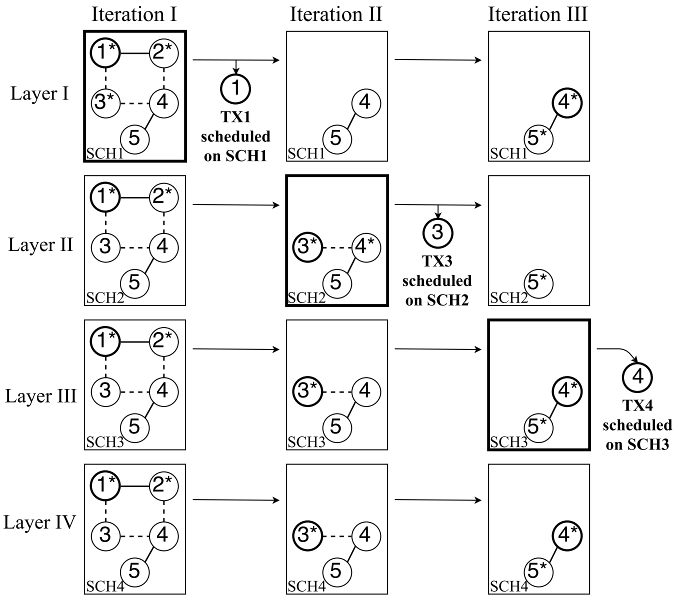


Fig. 2. Example of schedule computation. Each column corresponds to one iteration of the algorithm. Per each iteration, the transmission with the highest weight (bold circle) is scheduled on the currently selected SCH (bold square), and the suitable nodes are marked to be deleted. After the third iteration, all the layers are empty and the schedule is complete.

TABLE II

SIMULATION PARAMETERS

Content Request Modeling	
UDB size	30 elements
UDB item size	10 B to 1400 B
Process Intensity	$\lambda = 0.5\,\text{Hz}$
Information request interval	$T_{\text{req}} = -\log(U)/\lambda$
Road Network and Mobility Parameters	
Vehicular Mobility Traces	LuST Scenario v2.0 [12]
ROI Area	$1\,\text{km} \times 1\,\text{km}$
RSU Position	N49°36′38″ E6°7′34″
Low-Traffic scenario	from 04:00 to 05:00
Medium-Traffic period	from 17:00 to 18:00
High-Traffic period	from 18:00 to 19:00
Low-traffic vehicular density	$(26.48 \pm 8.71)\,\text{vehicles/km}^2$
Medium-traffic vehicular density	$(316.92 \pm 53.58)\,\text{vehicles/km}^2$
High-traffic vehicular density	$(404.27 \pm 29.51)\,\text{vehicles/km}^2$
Physical Layer Parameters	
OBU Transmission Power	$5\,\text{mW}$
OBU Receiver Sensitivity	$-89\,\text{dBm}$
Signal attenuation model	Free-Space Path Loss
Maximum transmission distance	$d_{\text{MAX}} \approx 250\,\text{m}$
Application Layer Parameters	
Beaconing period and lifetime	$T_{\text{BSM}} = 1\,\text{s}, \quad E_{\text{BSM}} = 1.2\,\text{s}$
ASK and TX Phases duration	$T_{\text{ASK}} = 1.8\,\text{s}, \quad T_{\text{TX}} = 0.2\,\text{s}$
Content caching lifetime	$T_{\text{INFO}} = 3\,\text{s}$

can define the priority (service weight) with which the i-th vehicle should be served as:

$$w_i = \frac{M_{\text{TX}}(i)}{C_{\text{RX}}(i) + 1} \in (0, +\infty) \tag{1}$$

where $C_{\text{RX}}(i) \in \mathbb{N}$ is the number of CONTENT messages received by the i-th vehicle, and $M_{\text{TX}}(i) \in \mathbb{N} \setminus \{0\}$ is the number of MIT messages sent by the i-th vehicle. The rationale behind Equation 1 is that vehicles that have sent several MIT messages (high $M_{\text{TX}}(i)$) and received few CONTENT messages (low $C_{\text{RX}}(i)$) should have higher priority when the RSU schedules senders for the following time slot.

b) ***Create a list of Tentative Schedules****:* According to the *network state information*, a list of potential V2V and I2V transmissions is produced and converted into a set of vertices of G. A potential transmission of the content item d from vehicle i to vehicle j introduces a vertex labeled $V_i d V_j$ in G, with weight w_j depending on the receiver.

c) ***Add hard and soft conflict edges to the graph****:* A labeled edge is added between nodes when transmissions can generate a conflict if they are scheduled at the same time. Conflicts can be divided into two categories: *hard conflicts* and *soft conflicts*, and each edge will be labeled accordingly to the type of conflict. A hard conflict exists between two transmissions that cannot be scheduled at the same time, even if allocated on different channels. A soft conflict exists between two transmission that cannot be scheduled on the same channel but that can be safely allocated on different channels.

2) Second Step: MLCG Creation and Schedule Computation: The second step of the ROADNET scheduling algorithm consists of creating the MLCG and computing the schedule. The schedule computation procedure is inspired by the Kako [10] greedy algorithm, which we modified to support multiple channels. The ROADNET scheduling algorithm is detailed hereafter, and an explanatory example is provided in Figure 2.

1) The master conflict graph G is replicated N times in an ordered list, where N is the number of SCHs ($N = 4$). Each replica is called *layer* and is associated with a single, distinct SCH (i.e. 174, 176, 180, and 182).
2) Per each scheduling period, a different *initial layer* is selected using the round-robin policy, so that all the channels are used equally.
3) In the *initial layer*, the node with the maximum $w_i/(d_i + 1)$ is saved in the scheduling table and is labeled as *selected transmission*. In this formula, w_i is the aforementioned Service Weight and d_i is the degree of the vertex in the layer.
4) The vertex corresponding to the *selected transmission* and all the vertices that are connected to it exclusively by a hard conflict are removed from all the layers except for the *initial layer*.
5) The vertex corresponding to the *selected transmission* and all its adjacent vertices are removed from the *initial layer*.
6) The *initial layer* is now set to be the next in the list of channels and the steps 3, 4, 5, and 6 are repeated until there is no longer a vertex in any layer of the MLCG.
7) The outcome of the process is a scheduling table containing the exact information that will be encapsulated in a TX message.

IV. SIMULATION SETTINGS

ROADNET and the CDD algorithm have been implemented and evaluated in Veins[1], setting the parameters of the different modules as reported in Table II. The particular choice of T_{ASK} and T_{TX} will produce a transmission schedule every $T_{\text{ASK}} + T_{\text{TX}} = T_{\text{S}} = 2\,\text{s}$.

A. Content Request Modeling

Each vehicle in the simulation can request, at a certain time, a certain piece of information, labeled with a unique ID. The set of all the possible content items that can be requested in the scenario is called *Universal information DataBase* (UDB). It has a fixed length of 30 elements with size uniformly distributed between 10 and 1400 Bytes.

Content items are stored in the UDB in descending order of popularity, following the Zipf's distribution, so that the elements on top of the list are considered to be "hot" and therefore have a higher chance to be requested. In order to determine which content item the vehicle requests when a content-request event happens, a non-closed form of the Smirnov transform [13] is used.

In real-world scenarios, vehicles request information neither constantly nor regularly in time. Hence, we assume that vehicles express *bursts* of content requests following a Poisson Process, with intensity $\lambda = 0.5\,\text{Hz}$. To quantify the time intervals between information requests, the Smirnov transform [13] has been used, leading to the closed form $T_{\text{req}} = -\log(U)/\lambda$, where $U \in (0, 1]$ is the output of a uniform number generator, and λ is the process intensity.

B. Road Network and Mobility

In the Veins environment, the Region Of Interest is a square centered on the RSU, which has been positioned in a well-known congested area of Luxembourg City centre. The performances of the two examined scheduling approaches have been evaluated under three different traffic conditions, corresponding to three different periods of the day and vehicular densities: low-traffic, medium-traffic, and high-traffic, as detailed in Table II.

V. PERFORMANCE EVALUATION

The collected data per each vehicle in each scenario are the total number of transmitted and received CONTENT messages per each SCH, and the total number of transmitted MIT messages.

A. Throughput and Fairness Metrics

The *throughput* is modeled as the number of all the relevant CONTENT messages received by the vehicles during the simulation, either from V2V or I2V. In order to quantify the *user fairness*, we have used the Jain's Index [14]:

$$J = \frac{\left(\sum_{i=1}^{N} x_i\right)^2}{N \sum_{i=1}^{N} x_i^2} \tag{2}$$

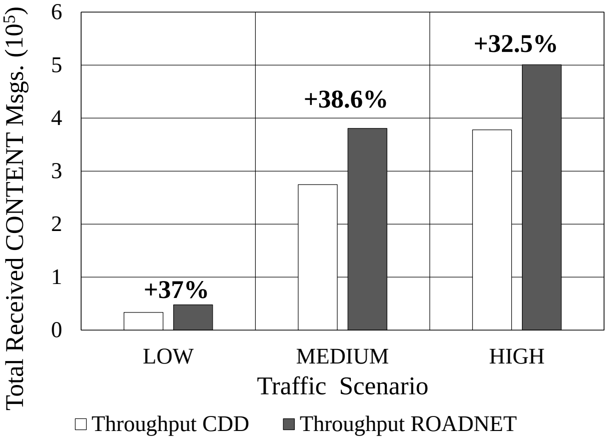


Fig. 3. Comparison of the content throughput performances between ROADNET and the CDD algorithm [3].

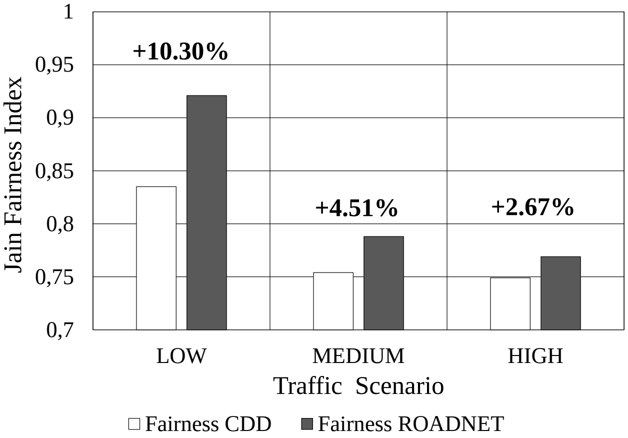


Fig. 4. Comparison of the user fairness performances between ROADNET and the CDD algorithm [3].

where J is the fairness index, N is the number of vehicles that have sent at least one MIT message, and x_i is the resource utilization for vehicle i.

The value of x_i represents the ratio between satisfied requests and total requests of the i-th vehicle. We define x_i as:

$$x_i = \frac{C_{\text{RX}}(i)}{M_{\text{TX}}(i)} \tag{3}$$

where $C_{\text{RX}}(i)$ is the number of CONTENT messages received by the i-th vehicle and $M_{\text{TX}}(i) > 0$ is the number of MIT messages sent by the i-th vehicle.

B. Results Analysis

1) Throughput and Fairness: Results show that ROADNET offers a sensible improvement in throughput because it employs four SCHs at the same time instead of just two SCHs as in the CDD algorithm.

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[1] Vehicles in Network Simulation: http://veins.car2x.org/

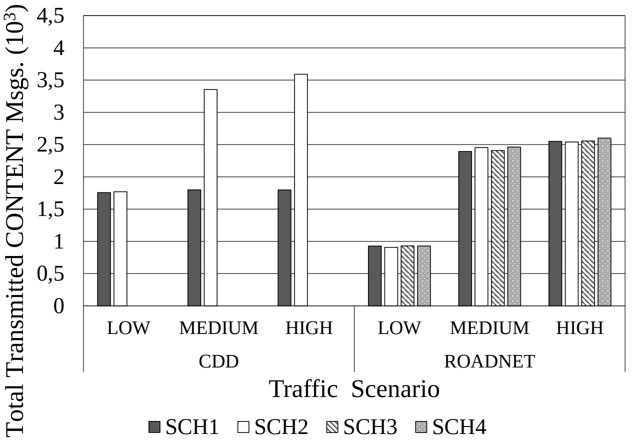

Fig. 5. Comparison of the channel load distribution between ROADNET and the CDD algorithm [3].

ROADNET also offers improved user fairness compared to the CDD algorithm, due to the fact that the weights in the MLCG are designed to favor those users who received less content items. By looking at Figure 4, it is noticeable that the fairness performance decreases as the vehicular traffic increases for both of the considered scheduling techniques. This is due to two main reasons. First, the beaconing congestion generates incomplete neighbor lists and prevents the RSU from having a global vision of the real state of the communication links in the VANET. Second, in the case of high vehicular density, the RSU must collect several MIT messages coming from the vehicles after it sends the periodic ASK message. Due to network congestion, some MIT messages are lost and, even if retransmitted, they might reach the RSU after their hard T_{ASK} deadline. Because of these two reasons, the RSU computes suboptimal schedules and we can consequently observe that, for high-traffic scenarios, ROADNET still offers a fairness enhancement over CDD, even though it is less pronounced compared to low-traffic scenarios. As a further step, a mechanism to implement flexible deadlines to collect MIT messages will be developed, in addition to a mechanism to integrate congestion avoidance of beacons and ROADNET messages.

2) Channel Load Balancing: As illustrated in Figure 5, the CDD algorithm presents a strong imbalance of the channel load distribution. Particularly in the medium- and high-traffic scenarios, we can notice that the SCH2 (exclusively dedicated to V2V communications) is drastically more loaded than the SCH1 (dedicated to I2V communications). On the contrary, we can observe that the standard deviation of the channel load on the different SCHs for ROADNET is around 1%. The reason behind the fair channel loading of ROADNET is the round-robin policy for selecting the SCH on which the selected content item will be transmitted.

VI. CONCLUSION

In this work, we have presented ROADNET, a cooperative scheduling scheme that balances data throughput and user fairness in VANETs. One novelty of ROADNET resides in prioritizing potential transmissions according to the user satisfaction ratio. Another innovation of ROADNET is the introduction of an SDN-based scheduling algorithm that provides optimized multichannel scheduling for V2X communications. After having analyzed the simulation outcomes, we have demonstrated that, in every vehicular traffic condition, ROADNET provides better global throughput and better user fairness compared to existing works, as well as a fairer distribution of the traffic load on the SCHs.

ACKNOWLEDGMENT

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